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RESEARCH ON PRICING
IN A GAS TRANSPORTATION NETWORK

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This report is focused upon regulatory institutions that organize prices within a network of commodity flows. The network has economic properties of the natural gas pipeline industry and the regulatory institutions have properties similar to those that are being considered as alternatives for the current rate hearing process. The questions posed at this stage of research are somewhat basic about the technical details of the institutions and how markets perform when they are in place. In order to isolate the independent effects of the institutions and separate them from many complicating economic activities that can occur in networks, it is best to begin with a study of relatively simple systems. It is also necessary to abstract from many important issues. For example, the legal details of the regulatory institutions are not addressed. Various uncertainties and complications resulting from uncertainty about commodity demand are not addressed directly. Such issues can be addressed by application of the same methodology, but at this stage of the investigation, they are not. The research strategy and overview of the study is contained in the first section.

Research Strategy and Overview

Four basic types of questions are posed by the research. The first type of question relates to the technical details of the regulatory institutions. Exactly how will the critical economic decisions be made? Who makes pricing decisions? Exactly what rules will be used? Who will be informed about what and when? What will be the timing of decisions relative to information? What commitment follows decisions? All of these questions are interdependent in the sense that the dimension of our question about technical details, the number of forms the question can take, depends upon the answers to other questions.

The second and third types of questions are related to market performance in the presence of the regulatory institutions. Are there economic forces which operate to circumvent the intended effects of market regulatory institutions in complicated networks? That the markets will work to move commodity at all is not obvious. Commodity flow through a pipeline network involves special coordination. The nature of the coordination changes as prices change along alternative routes. The interdependence inherent in networks would seem to be very important since high prices along one route could shift commodity flow to alternative routes. If prices along alternative routes are very sensitive to changes in demand and supply conditions, the ability of certain regulatory institutions to deal with the complexity can be challenged in terms of basic principles of market dynamics. Certainly thoughts of instability raise questions.

The fourth type of question addresses the sensitivity of any conclusions about market performance to the underlying parameters. Does competition make a substantial difference in market behavior? Is the structure of ownership or control important? What difference is caused by alternative costs and demands? Do slight changes in the regulations make critical differences?

Three basic types of regulatory institutions are investigated. The first type is a policy of administered prices that is adjusted by trial and error until a "satisfactory" price is found. During the trial and error phase, participants submit binding offers in response to the announced price, but all transactions take place only at the final satisfactory price. Such market institutions fall under a general terminology called "tâtonnement processes" as named by the inventor in the 1860s.[1]

The second type is a decentralized pricing policy (technically called the multiple unit double auction).[2] In this process, buyers and sellers of commodity and of transportation services

1) Leon Walras, *Elements of Pure Economics*

2) Plott and Gray, Social Science Working Paper no. 625. Pasadena: California Institute of Technology, March 1987.

are free to quote their own prices and adjust prices as they think best reflect their own circumstances and profit opportunities. The third type of regulatory institution is a process that has tested usefully in experiments that have interdependencies similar to those of pipeline networks.[3] The technical name is "Automated User Selection Mechanism" (AUSM). Because of its success in the related problems, it was a natural to try in the network.

Many combinations exist among the regulatory institutions, economic variables, and types of questions that might be asked. In almost all cases, neither previous experience nor previous experimentations can be used to provide answers. In a sense, all variables are relevant, but because there are so many combinations, a complete, balanced design which permits an empirical examination of all important cases is impractical for any reasonable time frame. A different approach was necessary.

A decision was made to follow a sequential research design to determine which types of regulatory institutions might make sense for policy discussions about the US industry. In this approach, a single experiment or sometimes a few experiments are used to determine the importance of certain variables. Favorable results would lead to more complicated experiments along the most promising directions. This research process leads to a rather complicated decision tree with decisions at some nodes based upon considerable judgment about what might be the ultimate results along some research branch if it were pursued. Such judgments are based on both theory and experience.

Section 1 reviews the first stage of research involving a study of a single market with no transportation. In the cases of some forms of market organization (MUDA and AUSM), that stage of research had been completed in other studies. There was no need for further research in a single market on those two types of institutions. The administrative trial and error process (tâtonnement) is different. Only one short study exists (Joyce 1984) and that study addressed none of the

3) Banks, Ledyard and Porter, Social Science Working Paper no. 648. Pasadena: California Institute of Technology, June 1987.

important details for the pipeline policy problem. The single market was a logical place to study tâtonnement. Single markets are less expensive and they are also less complicated so the nature of any difficulties can be identified and corrected by slight changes in policies or procedure. The single markets are a good place to find "bugs" in policies because in complicated multiple market networked systems the reasons for bad performance might not be easily identifiable.

Experiments and computer simulations were used to explore the technical details of tâtonnement processes. Many different price adjustment rules exist of which two were studied in detail. In addition, different rules for stopping the adjustment process and fixing a price to be used by the industry can be imagined and each of these must be appended with additional rules to prevent the process from stopping accidentally or getting locked into a divergent pattern of price changes. The appropriate information feedback to participants must be determined. For example, should total expressed demands and supplies be publicly announced, or should statistics based on the totals be announced, or should nothing be made public about the decisions of others? All of these very technical details can potentially interact with the decision behavior of participants, which in turn can affect the performance of the process. Theory does not give clear answers to such detailed questions so actual experiments must be conducted.

The sequential research design required that we study and modify policies in the context of a single market experiment until versions of the policies were obtained that were worth testing in multiple markets. The multiple market research would begin first with a small network with eight markets. This small network was actually part of a larger network (with nineteen markets) that was to be used to study regulatory institutions that lead to satisfactory market performances in the small network. Some marginal changes in demand and supply conditions were implemented across experiments, but the basic conditions of demand and cost were held constant.

Decisions were made to study a network which has some features that departed from the facts of the industry. This was done to present the regulatory institutions and the theories about their performance with a more extreme test than might exist in the field. For this reason, a decision was made to separate the ownership of transportation facilities from the ownership of commodity production. This separation presents a more difficult coordination problem than might exist if ownerships are combined. A single owner can transport commodity to markets without need to coordinate with others. Even though the combined ownership could be imagined to create monopoly problems, the issue of concentration and possible inefficiencies that stem from it is separable from the problems that can be caused by multiple and decentralized decision makers.

Similar logic resulted in a decision to conduct experiments in which no price controls existed. This differs substantially from the U.S. industry. Again, the reason for such a departure from the facts of the industry was to provide an adequate challenge to the process. Price ceilings and floors could obviously induce efficient behavior if set correctly (e.g., if set at the competitive equilibrium), but the successful operation of market regulatory institutions should not depend critically upon the existence of correct limitations on prices.

Experiments with the small network resulted in a decision to drop the tâtonnement processes from further study. Three experiments were conducted. None ever terminated in a pattern of prices that permitted trade. The exact reasons for the failure of this type of regulation are unclear, but conjectures advanced in the body of the report are based upon strategic behavior that can exist within the policy.

Similarly, experiments with the small network led to a decision to drop AUSM from further consideration. The network configuration and the nature of the technical generalizations of AUSM required to accommodate the facts of the network opened the way for potential profits from strategic behavior. If this particular type of strategic behavior was followed by enough people, it would lead to no trade at all. In fact, the strategic behavior was far beyond that sufficient to make the system break down. Without any obvious "quick fixes" close at hand, a decision was made not to continue the line of research.

Experiments with MUDA in the small network yielded sufficiently satisfactory results to justify a challenge to that type of regulatory environment with a tougher test within the larger network. The several experiments in the small network and several series of experiments in the larger network provided lessons about the organization of so many markets and in the nature of computerized multiple market systems. All of these lessons are captured in the final series of experiments. Consequently, only one series, the final series, is reported in the body of the text because it summarizes the lessons from all of the others. In this series, competition was created along all segments of the pipeline. Every two points were connected by two competitive pipelines, neither of which had the capacity to serve the whole demand at competitive prices. Under such competitive circumstances, the prices approximated the competitive equilibrium prices, and market efficiencies ranged in the 70 and 80 percent level. While these efficiencies are not high relative to what is observed in single markets, they are much better than the other types of market regulations which did not work satisfactorily at all. Efficiencies increased as participants gained experience with the process and got as high as 90 percent.

After a larger group of participants had experience with the network, participants were chosen at random to participate in the same pipeline system with monopolized segments. All conditions were identical, except along every segment, capacities were merged into a single transportation supplier. The number of suppliers was reduced from six suppliers over ten segments to three suppliers, which collectively supplied the ten segments. Each segment had only one supplier. The result was a decrease in efficiency and a shift in the *relative* distribution of income away from commodity producers and consumers to the pipeline companies. However, the drop in efficiency was such that the absolute level of profits of transporters was not increased over what prevailed under competition.

SECTION 1: SINGLE MARKETS:

Administered Trial and Error Pricing (Tâtonnement) in a Single Market

Experimental work has shown that under favorable conditions an administered trial and error process (tâtonnement) will converge to an equilibrium price (Joyce 1984). However, it is not known that such prices will converge under the particular type of economic circumstances that are thought to exist in the natural gas pipeline industry. This section examines two types of tâtonnement processes and reports on their behavior in a single market. The market has some of the relevant and difficult characteristics of the industry.

In all experiments, demands and supplies were induced through financial incentives. The technique has been widely used (See Smith 1982, Plott 1982). The special features of the industry that might cause problems are the constant cost of transportation and the inelastic demand. Together, these features almost guarantee the lack of existence of an equilibrium price in the classical sense; that is, a price at which the quantity desired as demand exactly equals the quantity desired as supply. Figure 1, which reflects the parameters actually used in some of the experiments, demonstrates the problem. At the price $P_o = 195$, the desired demand is $D_o = 16$, but the desired supply is $S_o = 35$.[4] If prices are slightly above P_o, supply exceeds demand and, if prices are slightly below P_o, demand exceeds supply. At no price does quantity demanded equal the quantity supplied. If an administrator sees only the expressed demand and the expressed supply, then he could never find a price that equated the two. If the rule given to the administrator for adjusting prices did not have special features to deal with the problem or, if individual decisions in the process of adjustments did not adjust to help solve the problem, then the administrative process could cycle forever with no satisfactory termination.

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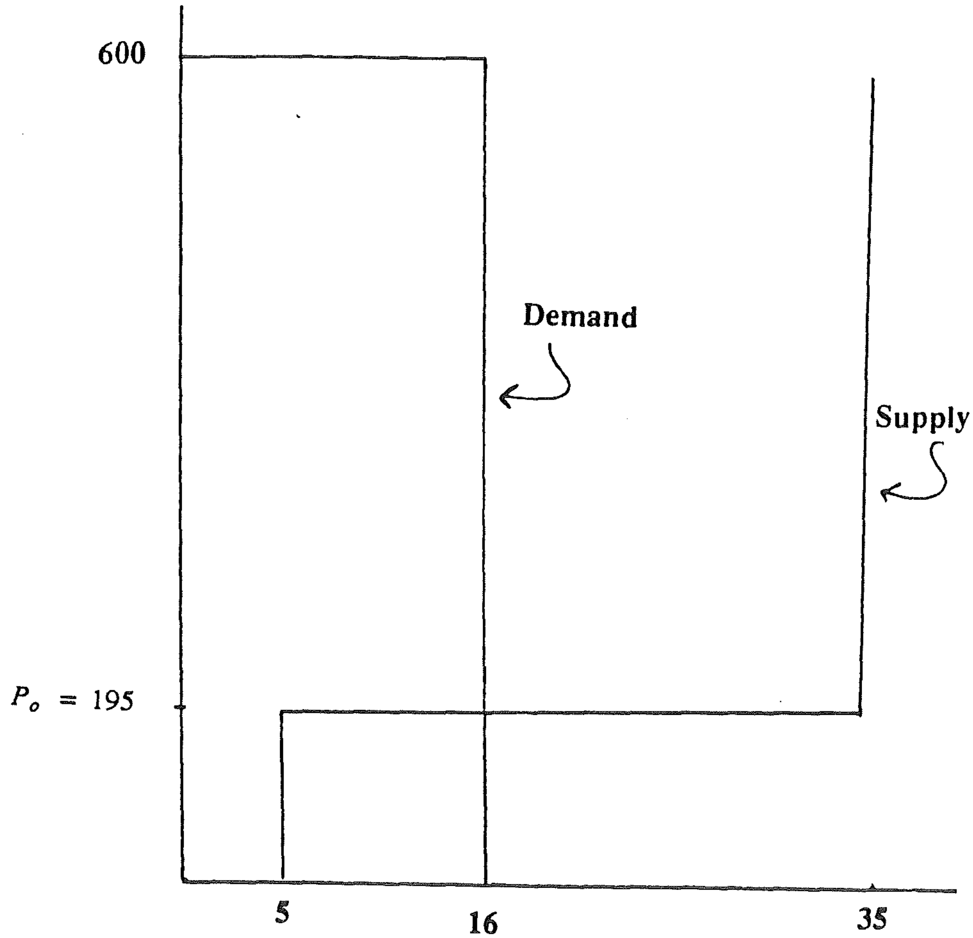
4) In a Debreu (1959) sense, an equilibrium exists because suppliers are indifferent among all quantities from 0 to S_o. Thus, the quantity D_o can be viewed as the supply as well as the demand. At P_o, both demand and supply are D_o, so quantity supplied equals quantity demanded. However, if the flat supply is caused by a price floor, the Debreu argument does not hold. Nevertheless the Debreu concept of equilibrium seems to apply as a model of behavior.



Parameters Used in Experiment 4

FIGURE 1

The two tâtonnement processes studied in this section differ by the mechanical features used to determine price changes. They also differ by the rule for stopping price changes and deal with the problem above.

Two price change rules are explored. Let

ED_t = Expressed quantity demanded at period t, minus express quantity supplied at period t.

$= D_t - S_t$

(1) (The Secant Rule)

$$P_t = \begin{cases} P_{t-1} + \left| \dfrac{P_{t-1} - P_{t-2}}{ED_{t-1} - EDt-2} \right| ED_{t-1} & \text{if } ED_{t-1} \neq ED_{t-2} \\ P_{t-1} + (P_{t-1} - P_{t-2}) & \text{if } ED_{t-1} = ED_{t-2} \end{cases}$$

(2) (The Proportional Adjustment Rule)

$$P_t = P_{t-1} + \alpha\, ED_{t-1} \qquad \alpha > 0$$

While both the Secant Rule (1) and the Proportional Adjustment Rule (2) specify methods for price *changes*, neither rule specifies a method of actual price determination; the price at which trades are made. The following performs that important function. The system stops if

(3) $P_t = P_{t-1}$

Equation (3) can be satisfied in two ways. Either (3.1) $ED_{t-1} = 0$ or (3.2) the ratio $\dfrac{P_{t-1} - P_{t-2}}{ED_{t-1} - ED_{t-2}}$ gets so small relative to ED_{t-1} that the precision of the calculation (usually 10^{-4}) is insufficient to record a change. When either event occurs, the process stops and the price is set.

Both processes were simulated under a variety of demand and supply conditions. These simulations are contained in Appendix A. Convergence always occurred even in the cases of nonexistence of the equilibrium P. The numerical methods implied by (1), (2), and (3) simply "fill in" holes. Of course, when the system stops at a "pseudo" equilibrium, such as P_o in the figure, some sort of rationing would be necessary. The quantity demanded and supplied would not be in balance even though the price is "efficient" and no price would be "better." Special care must also be taken to ensure that the "efficient" price is chosen because slight errors in price could result in big errors in trades. For example, if the system stopped at a price slightly above P_o, the volume would be 16, but if the price were slightly below P_o, the volume would drop to 5.

Process Procedures

The process is described by the following set of rules.

1. Agents were located such that no means of communication was possible.
2. The process began with an initial price made public to all agents.
3. Each agent transmitted a quantity that he/she wanted to buy or sell at that price.
4. The sum of individual demands and the sum of individual supplies were made public.
5. A check was made to determine if the system should terminate.
6. If the system terminated, trades were made at the existing prices. If rationing was necessary, it was accomplished randomly.
7. If the system did not terminate, a new price was calculated using the appropriate rule. The new price was publicly announced. Such an iteration was called a *trial.*
8. The rules for price changes and terminations were public knowledge.
9. Records of all public information were maintained publicly.

Experimental Procedures

A series of six experiments were conducted. Each consisted of a series of periods in which a price determination was made and trades took place. The individual parameters remained the same from period to period in some experiments and in other experiments they changed each period.

Experimental Results

All six of the separate experiments were conducted under the secant process. These operated under a variety of different conditions. The results of all experiments are in Appendix B. Figure 1 contains the demand and supply parameters for Experiment 4. The final price, the final expressed demand and supply quantities, the number of iterations until stopping, and the stopping rule used are in Table 1. This experiment is useful because it demonstrates much of the phenomena seen in the more extensive experiments. For example, the appendix contains experiments with ? Markets conducted in sequence with parameter changes allow a check on the ability of the process to respond to changing conditions.

Several properties of the data from Experiment 4 are of interest. First, every period resulted in a final price. Notice, however, that this final price is not the same price even though each period the underlying demand and supply parameters are the same. Final price changes, even though the economic conditions do not (e.g., compare the Period 3 price of 365 to the Period 4 price of 196). Notice also that the number of trials needed for convergence changes from period to period. These differences reflect attempts by agents to manipulate the process.

Of particular interest are the stopping rules. In every period except Period 4, the system stopped because expressed demand equaled expressed supply even though such equilibrium does not exist theoretically. More importantly, a close look at the numbers reveals that volumes in some periods (2, 3, and 7) are *above* the maximum possible demand of sixteen. Agents are purchasing units for which they have no use. Such purchases are a pure loss incurred in order to get the process to stop iterating.

Notice that the process can stop with demand and supply unequal (Periods 1 and 4). In these periods, available demand must be rationed among the suppliers.

TABLE 1: Single Market Tatonnement #4

1. Parameters—4 equal buyers and 7 equal sellers

Demand Price	Quantity	Supply Price	Quantity
601	0	196	35
600	16	195	35
0	16	194	5
		0	5

2. Equilibrium—none exists

pseudo equilibrium $P_0 = 195$

3. Final Results

Period	Price	D	S	Stopping Rule	No. of Trials
1	325	18	20	rounding	19
2	197	20	20	$D = S$	18
3	365	17	17	$D = S$	4
4	196	15	21	rounding	17
5	196	15	15	$D = S$	19
6	202	17	17	$D = S$	21

Analysis

1. Divergence from the "pseudo" equilibrium price in experiments (see Experiment 5 in Appendix B) demonstrated the need to add the absolute value as contained in the term in (1). This addition assumes that demand curves are always downward sloping and that supply curves are always upward sloping.

   The absolute value term helps eliminate a problem caused by random behavior, by strategic behavior, and by boundary behavior problems. Unlike analytic functions, human behavior is not the same whenever a given price is repeated more than once. People try to manipulate the system to obtain a better deal for themselves. Or, they may be attempting to get the process to converge so they can undertake the transaction and make money. Sometimes the process results in price quotations that are not taken seriously, so people do not bother to respond or respond with nonsensical amounts. For all of these reasons, responses do not occur with constant mathematical precision.

2. Convergence occurs. All single market experiments converged after the absolute value term was added to the rule.

3. Convergence was due to strategic behavior of participants and not because of the "filling in" property of the process. In order to see this, notice that all experiments terminate at a P because $ED = 0$ at that P, even though, theoretically, such a P does not exist. People adopted strategies that they believed would help the process converge.

   Profits are made only when the process stops at an equilibrium. Trades take place only when the process stops. Thus, people have an interest in stopping the process.

4. Efficiency was not 100 percent. This results from buyer purchases of units for which they had zero redemption value. The theoretical possibility that the process stops with no trades never occurred.

5. Good information feedback to participants about expressed demands and supplies might be necessary for convergence. This conjecture is suggested by the fact that information seemed to be used by participants to get the process to stop. Sellers who held back from the competitive response and buyers who purchased more than the competitive response needed to make such responses strategically to match the offers of each other. Such strategies require information. Without the information, strategic play would probably be reduced but in that case the incidence of successful convergence would also be reduced.

   In the simulations presented in Appendix A, no such information was used. Buyers and sellers responded competitively. As a result, stopping was due to a gradual diminution of price changes until the rounding precision of (3.2) was exceeded and no price change occurred. This particular rule may not be reliable with people making decisions because human decisions reflecting mistakes, frustration, search or slight adjustments in strategies are always present. Such adjustments may be sufficient to prevent convergence.

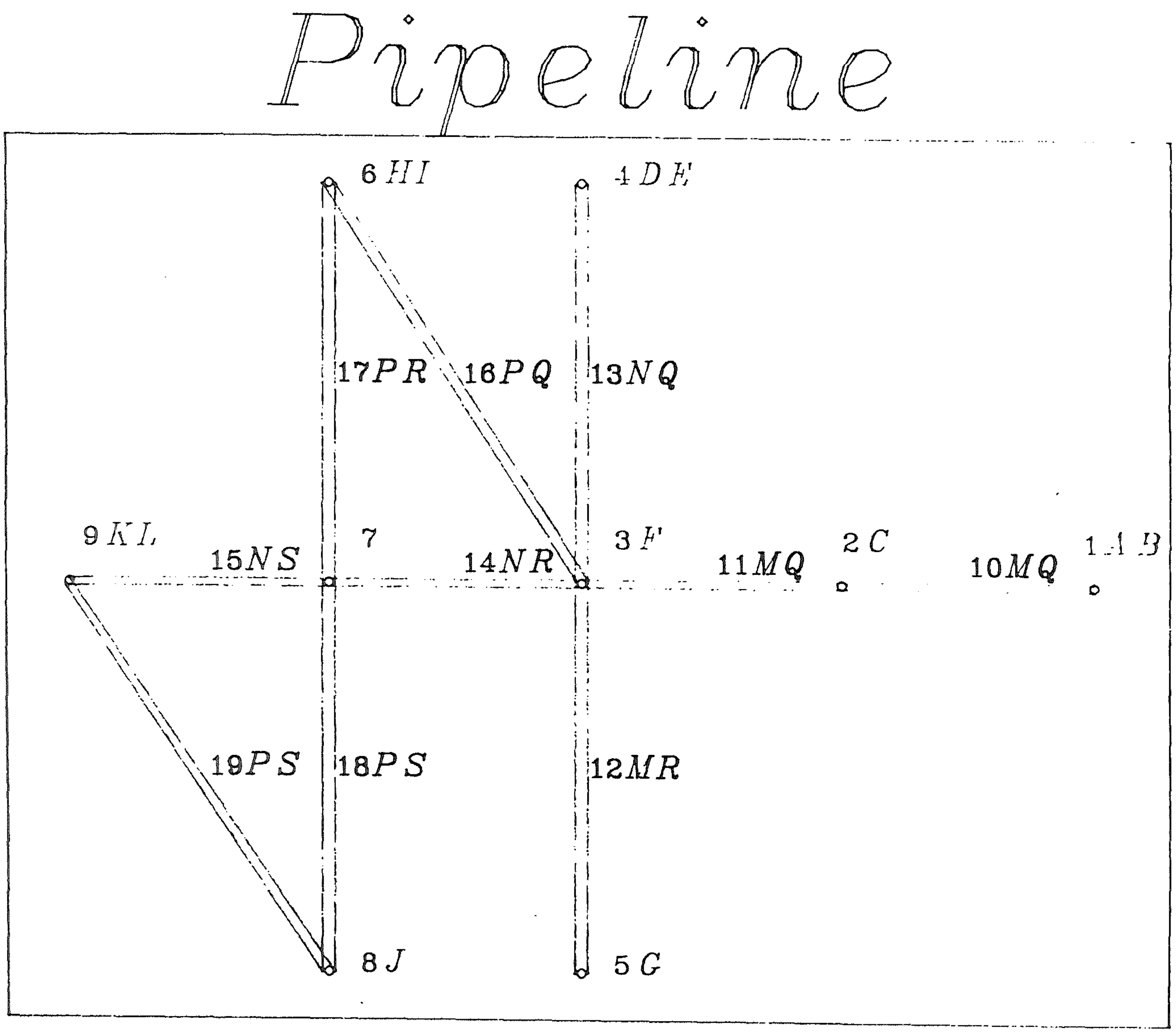
   Algorithms that anticipate stochastic features of systems do exist. However, they depend upon some sort of averaging process which creates (theoretically) room for profitable manipulation. Because of this potential difficulty, such classes of process were not pursued.

SECTION 2: THE SYSTEM NETWORK

Two networks are studied. The largest network is shown in Figure 2. The nodes are site specific locations called points. Such points are the locations of either producers (e.g., points P1, P3, P6) or consumers (e.g., P2, P4, P5, P8, P9). The arcs connecting the points (called lines) represent the locations of pipelines. A given pipeline company might operate over several different lines (e.g., one company might own pipelines over lines L10, L11, and L12).

The smaller network which was used for initial tests of policies is shown in Figure 3. This network is simply a subset of the larger network. In particular, the smaller network was the left-hand portion of the larger network consisting of points P6, P7, P8, and P9, together with connecting

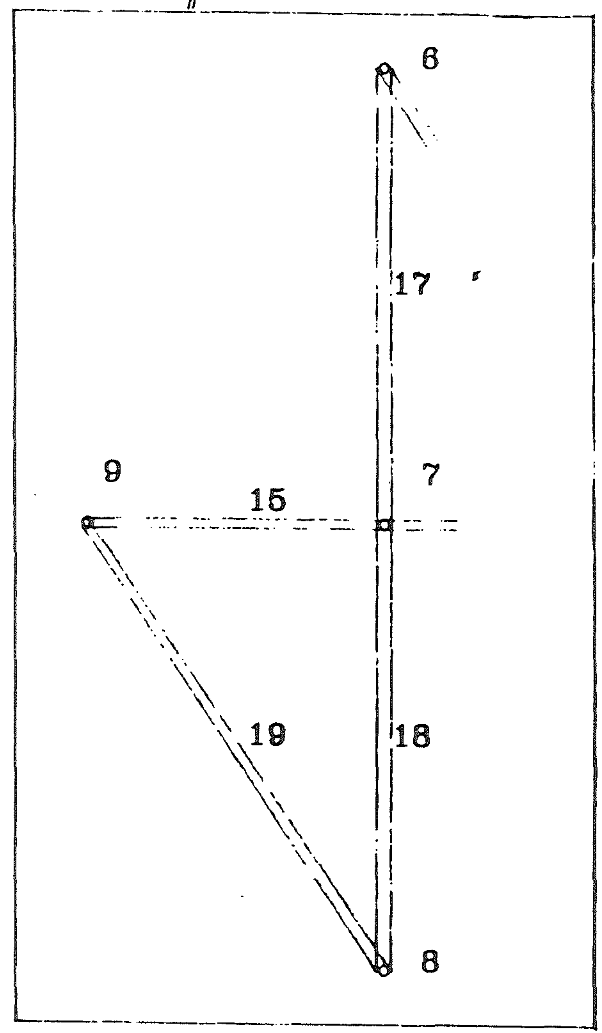
FIGURE: 2



Large Pipeline Network

FIGURE: 3

Pipeline



Small Pipeline Network

lines L15, L17, L18, and L19.

The important economic parameters are the number, location, and capacity of consumers, gas producers, and pipelines. In addition, the ownership of gas production wells and pipelines are variables.

Demands and costs were again induced by monetary incentives. The nature of these incentives was adapted to the network. Consumers are given redemption values for units consumed. They are able to keep as earnings the difference between the redemption values of units consumed and the amount spent acquiring and transporting the units. Gas producers are given cost schedules. Their profits are the difference between the cost of production plus any transportation expenditures and the income received from the sale of commodity. The costs considered are only variable costs, since capacity expansion is not allowed, capital cost and related expenses are not relevant for the problem. Similarly, pipeline owners are given a variable cost of transporting commodity through their pipelines. Each pipeline is treated as a separate facility with flow over one segment having no influence on the cost of transporting commodity over a different segment. The profits of transporters were the difference between the revenue received from transportation fees and the cost of transport. Depending upon the policy, participants might also profit from buying commodity in one market and either reselling it in the same market or transporting it to another market for sale.

The demands and costs were chosen to have some of the properties of the industry. Some consumers had very inelastic demands at prices near the competitive equilibrium while others had elastic demands. Producers and pipelines had flat costs up to a capacity limit after which cost became steep.

The actual parameters for the full network and the small network are in Tables 2 and 3. The redemption values are stated in units called francs. Thus, all transactions are quoted in terms of francs. The franc/dollar conversion rates are also given in the tables. The convention of using francs permits the study of identical economic situations with the same participants without the

TABLE 2: Parameters for Experiments on Large Network

Location	Agent	Type	Cost/ Redemption	Comp. Price	Comp. Value	Comp. Profits
P1	A	Producer	130,5 152,4	157	8	150
	B	Producer	130,5 152,4		8	150
P2	C	Consumer	207,4 105,4	177	4	120
P3	F	Consumer	230,6 203,4	190	10	292
P4	D	Producer	130,5 160,4	165	7	185
	E	Producer	130,5 160,4		7	185
P5	G	Consumer	230,4 210,2	206	6	104
P6	H	Producer	140,5 170,4	200	9	420
	I	Producer	140,5 170,4		9	420
P7		Nothing		231		
P8	J	Consumer	280,6 250,4	245	10	230
P9	K	Consumer	300,4 270,4	252	9	264
	L	Consumer	295,4 265,6		9	250
L10	M	Pipeline	10,8 15,3	20	8	80
	Q	Pipeline	10,3 15,3		8	80

TABLE 2: Parameters for Experiments on Large Network (cont.)

Location	Agent	Type	Cost/ Redemption	Comp. Price	Comp. Value	Comp. Profits
L11	M	Pipeline	5,6 8,3	13	6	48
	Q	Pipeline	5,6 8,3		6	48
L12	M	Pipeline	6,3 11,12	16	3	30
	R	Pipeline	6,3 11,12		3	30
L13	N	Pipeline	14,7 20,3	25	7	77
	Q	Pipeline	14,7 20,3		7	77
L14	N	Pipeline	29,4 36,3	41	4	48
	R	Pipeline	29,4 36,3		4	48
L15	N	Pipeline	11,4 16,3	21	5	50
	S	Pipeline	11,4 16,3		5	50
L17	P	Pipeline	19,7 27,3	32	10	106
	R	Pipeline	19,7 27,3		10	106
L18	P	Pipeline	4,7 8,3	13	9	73
	S	Pipeline	4,7 8,3		9	73
L19	P	Pipeline	5,4 9,3	10	4	20

S	Pipeline	5,4 9,3	4	20

TABLE 3: Parameters for Experiments on Small Network

Location	Agent	Type	Cost/Redemption	Comp. Eq.	Comp. Alloc.	Comp. Profit
P6	A	Producer	110,6 170,2			
	B	Producer	110,4 170,6			
P7	C	Producer	230,2 240,4 250,4			
P8	F	Consumer	340,6 310,4			
P9	G	Consumer	430,4 240,4			
	H	Consumer	360,4 310,4			
L15	E	Pipeline	20,12 30,6			
L17	D	Pipeline	30,16 50,6			
L18	D	Pipeline	20,10 30,6			
L19	D	Pipeline	30,12 50,4			

participants becoming aware of the similarities because the units are different. The tables are read as follows. Starting at the top of Table 2, the reference is P1 at the far right-hand point of Figure 2. Agent A is located there as is Agent B. Both are producers and their variable costs are the same. The marginal cost of producing is 130 for the first five units that A produces and it jumps to 142 for four more units. The total capacity of A is nine units.

The Competitive Equilibrium Model

A standard of measurement of performance of a policy is efficiency. If cost/benefit theory is applied, the social optimum occurs when agents as a group (consumers, producers, and pipelines) have earned the maximum possible profits given the economic constraints. The efficiency of the system operating under a policy is the ratio of actual profits of participants divided by the maximum possible profits. In other words, if the system is operating at 25 percent efficiency under a policy, the participants are as a group earning 25 percent of the maximum possible.

A standard behavioral model of a process is the competitive equilibrium price vector and allocation vector. In the networks studied here, many different competitive equilibria exist. For purposes of comparison, a "natural" one was chosen[5] and is given in the table for each market and agent. To continue the first line of Table 2, as an example, the competitive equilibrium price for commodity delivered at A is 157. In equilibrium, A will produce and sell eight units for a profit of 150.

SECTION 3: TRIAL AND ERROR ADMINISTERED PRICES (TATONNEMENT) ON MULTIPLE MARKETS

The administered process (tâtonnement) was first implemented in the small network of Table 3. Both the secant process and the proportional rule explained earlier were applied. When problems were encountered, an attempt was made to implement a less flexible policy in which

5) Both producers and pipeline owners receive a five franc profit per unit over the marginal cost and all other rents are captured by consumers. Allocations of identical individuals are the same.

transportation charges were derived as the difference between the prices at connecting points. Nothing worked.

The processes were implemented by a networked computer. Agents entered decisions at their own computers and prices were announced on each display screen. The first attempt had the following major features:

(1) A separate market existed for each economic variable. That means a separate price existed for commodity delivered at each location point. A separate price also existed for each line.

(2) The process began with an initial price announced for each market.

(3) All agents submitted the quantities of commodity they desired at each location and the quantities of transportation services they wanted to use along each line.

(4) Commodity producers reported the quantity they were willing to supply at each location given the announced commodity prices and transportation charges.

(5) Pipelines announced the capacity they were willing to supply along each line given the announced transportation prices.

(6) Any agent could engage in arbitrage by purchasing commodity at one location, purchasing the necessary transportation, and selling the transported commodity in another location (or consuming it in the case of consumers).

(7) The computer checked to see if demands and supplies balanced. If not, and if one of the other stopping rules was not applicable, new prices were calculated and displayed.

(8) The price in each market was calculated independently by the Secant Rule (1). In later experiments, the Proportional Rule (2) was used.

(9) All markets remained open until all markets had simultaneously equilibrated.

(10) Special techniques[6] were used to keep isolated markets open when they had equilibrated

6) A distinction was made between calculated prices and reported prices. Only integers were reported, but calculated prices were computed with precision to 10^{-8}. When price changes were so small that greater degrees of precision were needed, or when excess demand was zero, the markets would close. When this happened, the market was kept open by a "kick-start" procedure of letting $\Delta P = 1$.

before the other markets.

(11) Each agent had a record of all previous prices for all markets, the previous excess demands in all markets, and his own decisions in all markets.

Network Tâtonnement Experiments

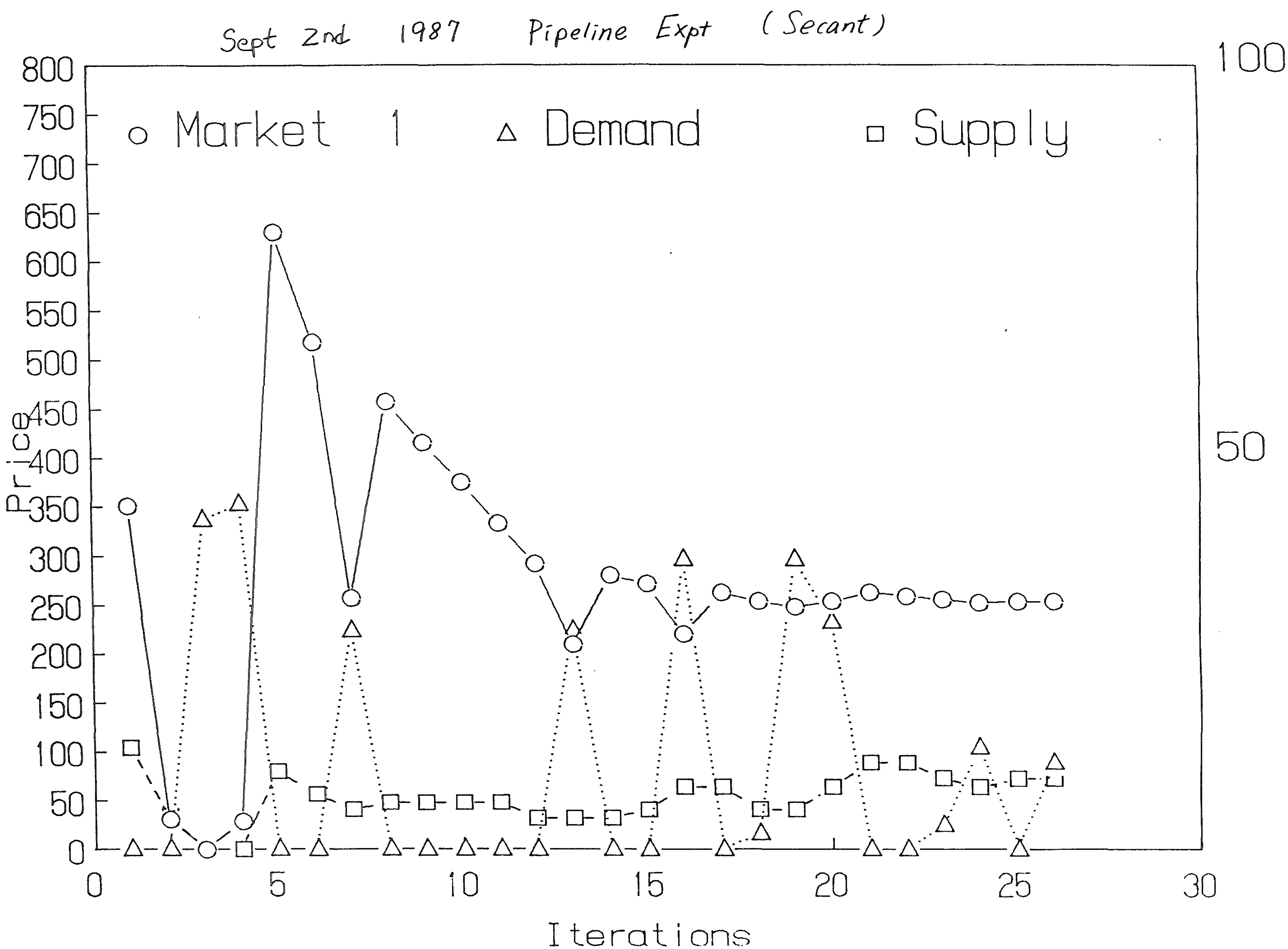
Several experiments were conducted before the details of a consistent policy could be formulated. The need to keep markets open became clear early. Markets might temporarily equilibrate, but then need to disequilibrate as the convergence process in the remaining markets foster changes in traffic flows. If the rules for single, isolated markets are applied, and as a result, the market equilibrates too early, then the price can become fixed at prices that generate excess supplies or excess demands when the other markets in the network finally reach an equilibrium.

The problem can be severe. For example, a pipeline market that should be operating at the margin of capacity at high prices in competitive equilibrium might have very little demand while upstream pipelines are at disequilibrium prices that are much too high. If the disequilibrium is not corrected quickly the market in question might equilibrate at a fixed price too low to stimulate the use of the marginal capacity which is actually needed to accommodate equilibrium traffic flows.

The problem of inappropriate equilibration can also be a result of behavioral phenomena. If prices are so high that no demand is expressed, a seller might not bother to offer a supply. Since $D = S = 0$, the market can accidentally equilibrate at a price that is too high.

After the technical details of the process were worked out, several experiments were conducted. Figures 4-A through 4-H report the results in one conducted on September 2. The labeling of markets as represented in Figure 3 is changed for the purpose of the experiments. The markets labeled 1, 2, 3 and 4 are the three points labeled clockwise starting from the top. The pipelines were labeled Markets 5 through 8 in clockwise fashion beginning with the top. Each page is a different market.

FIGURE: 4-A



Sept 2nd 1987 Pipeline Expt (Secant)
Market 1
Demand
Supply
Price
Iterations
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
5
10
15
20
25
30
50
100

FIGURE: 4-B

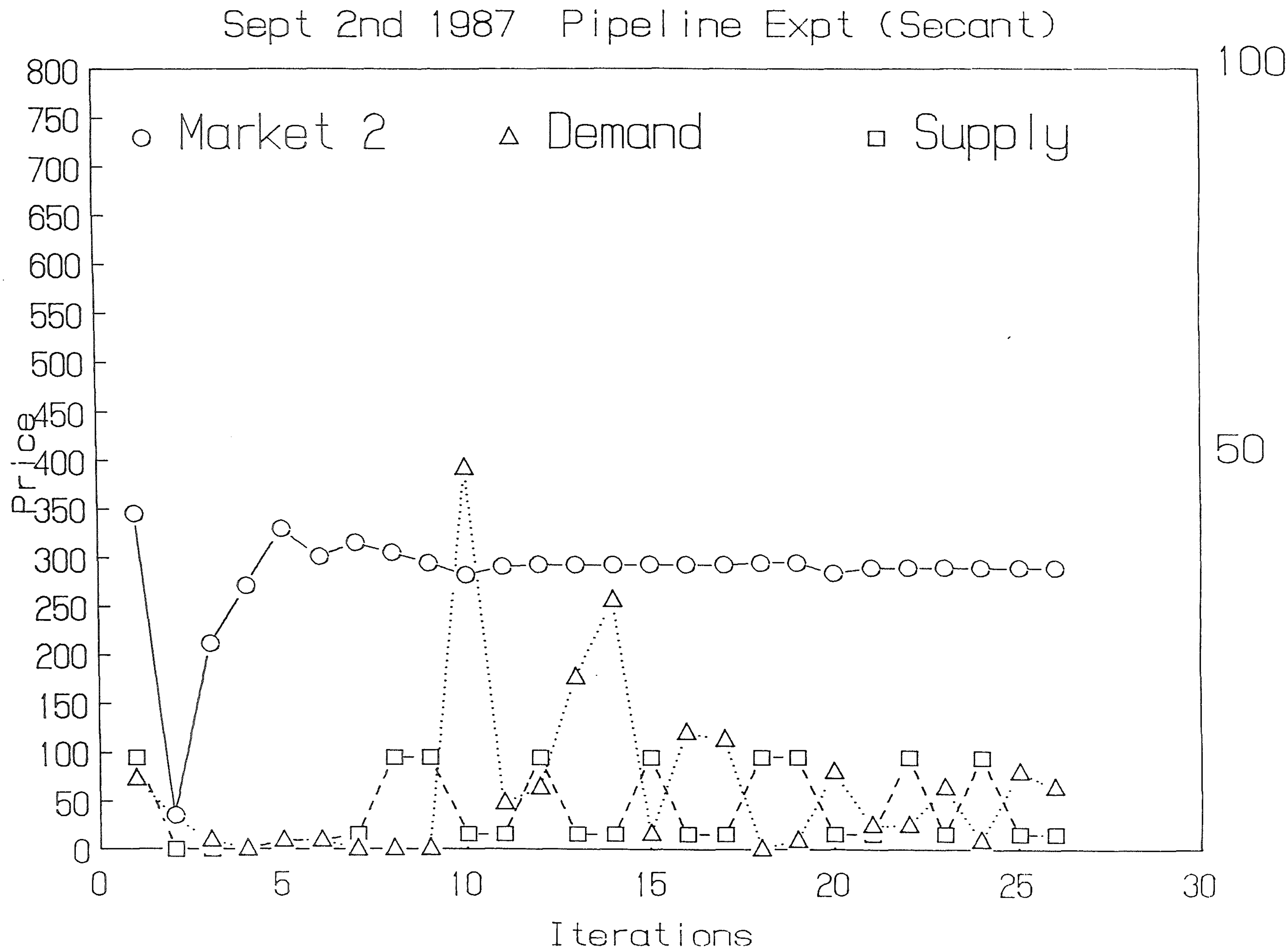
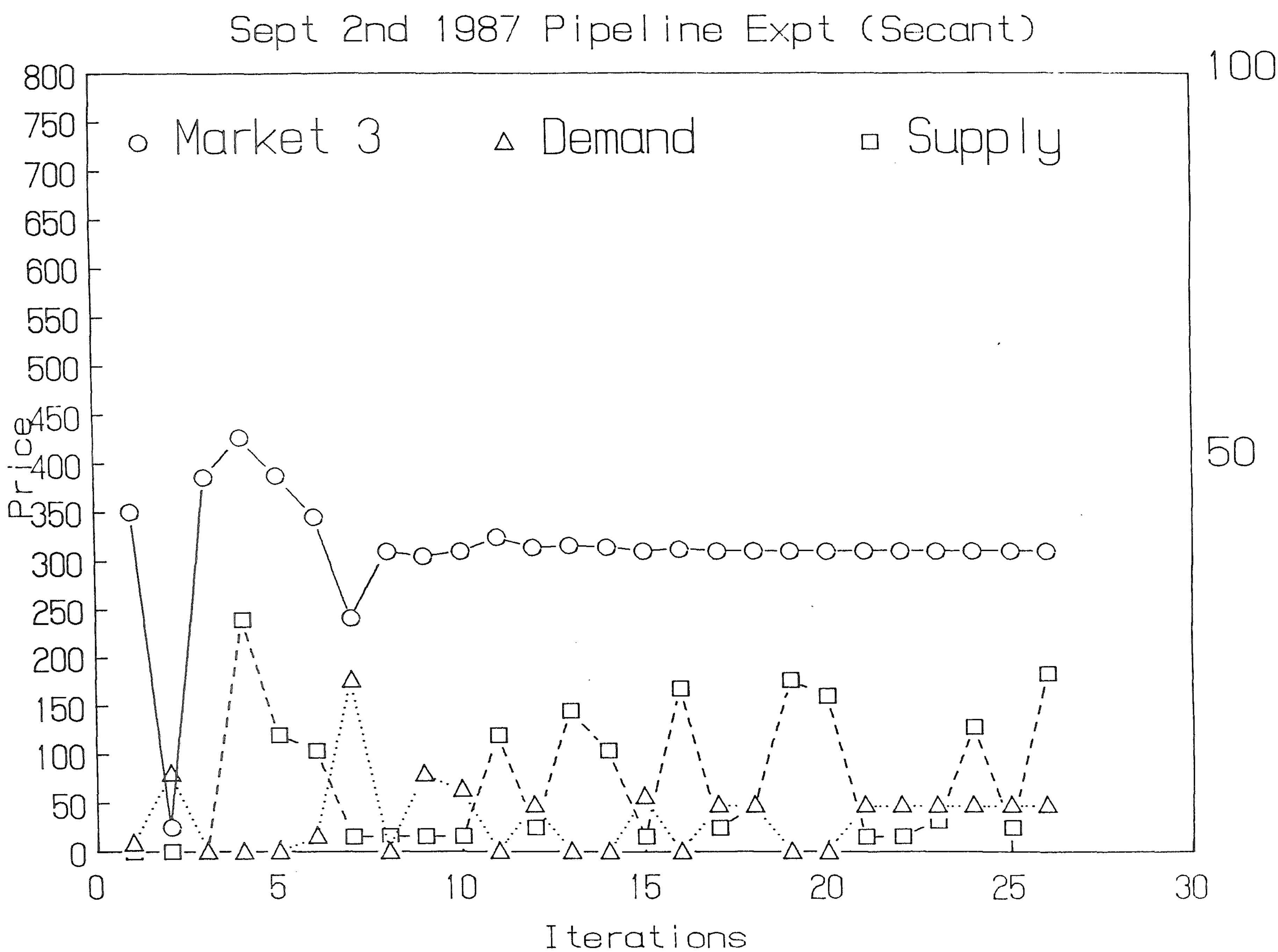
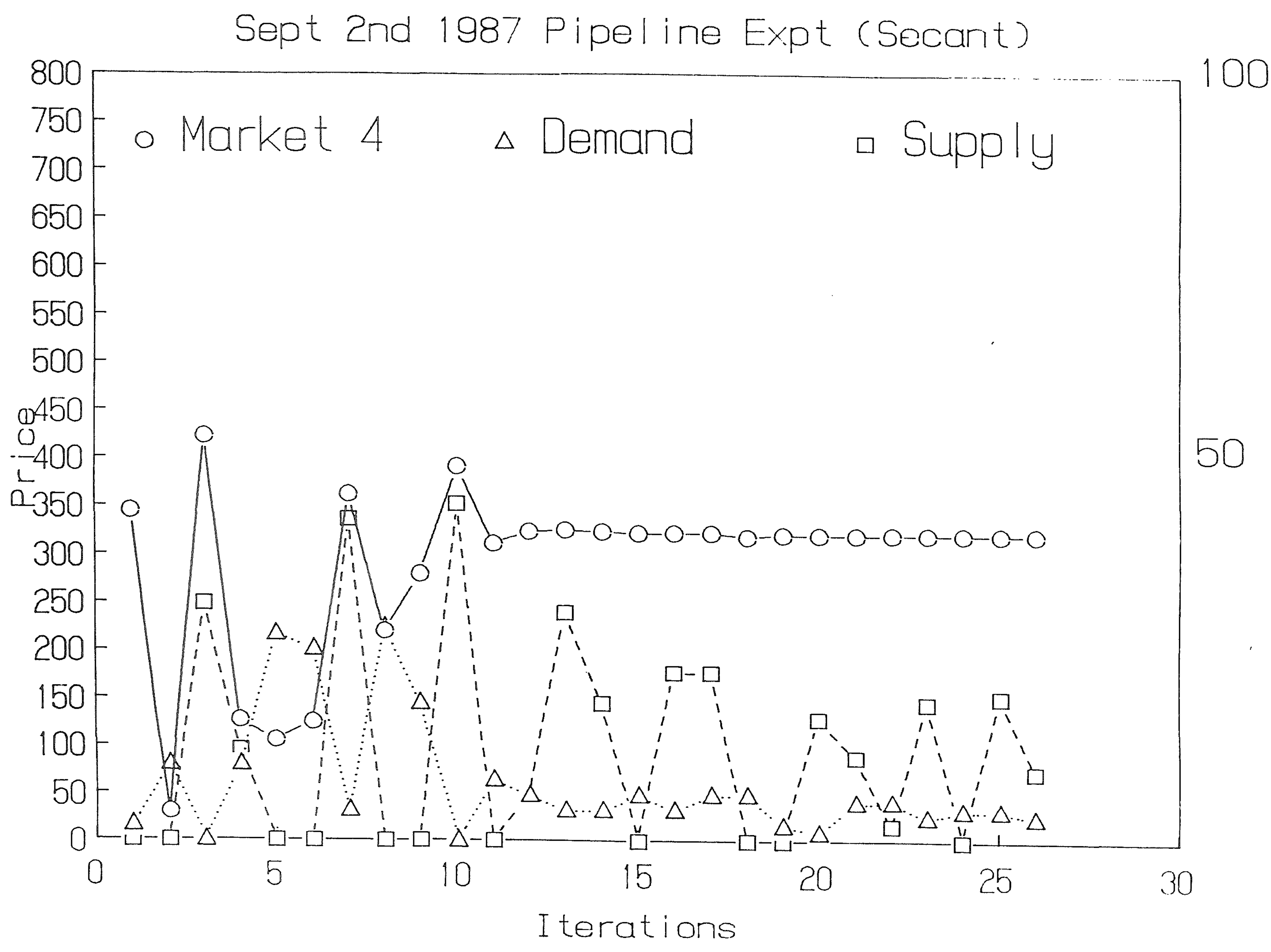

Sept 2nd 1987 Pipeline Expt (Secant)
Market 2
Demand
Supply
Price
Iterations
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
100
50

FIGURE: 4-C



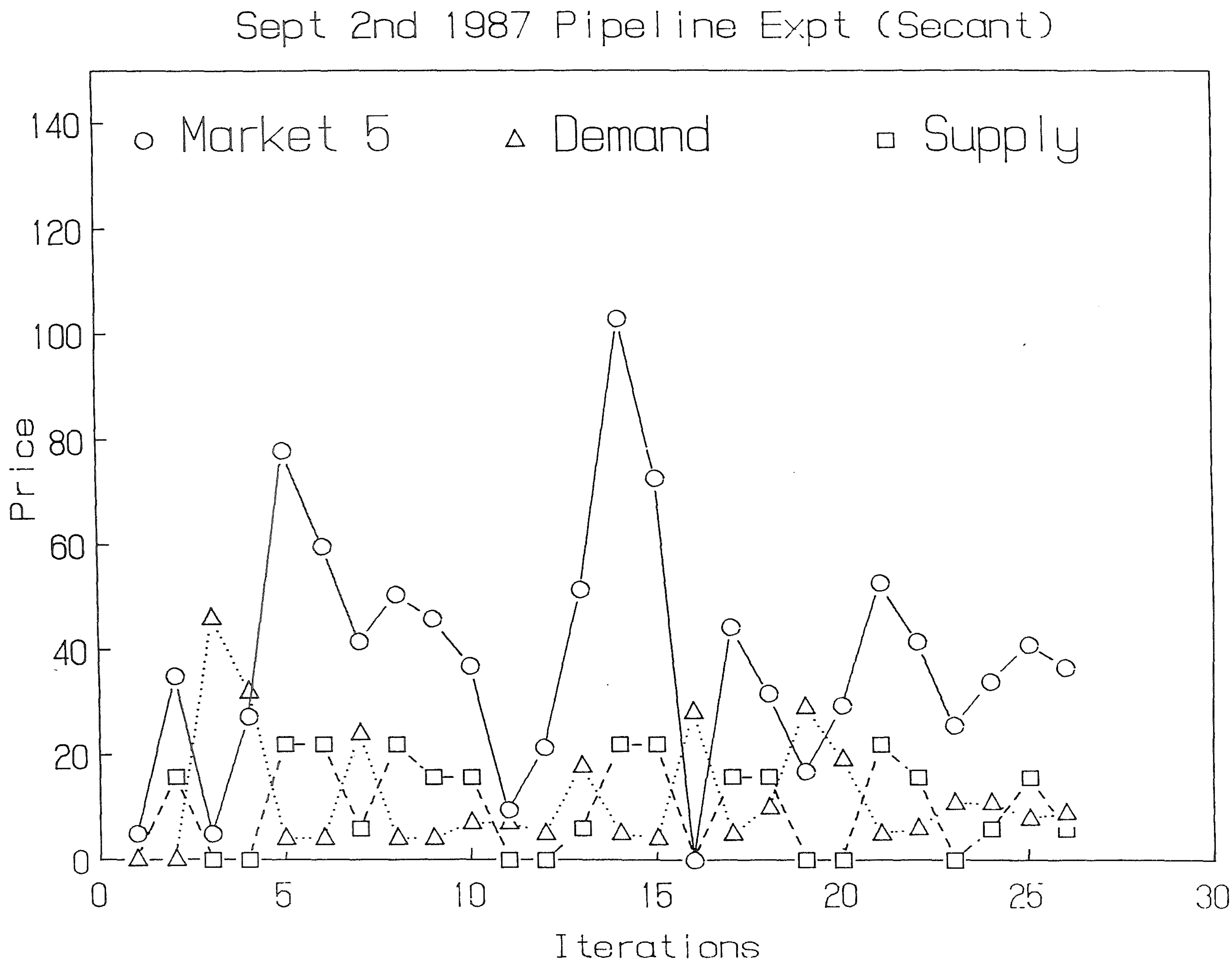
Sept 2nd 1987 Pipeline Expt (Secant)
Market 3
Demand
Supply
Price
Iterations
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
5
10
15
20
25
30

FIGURE: 4-D



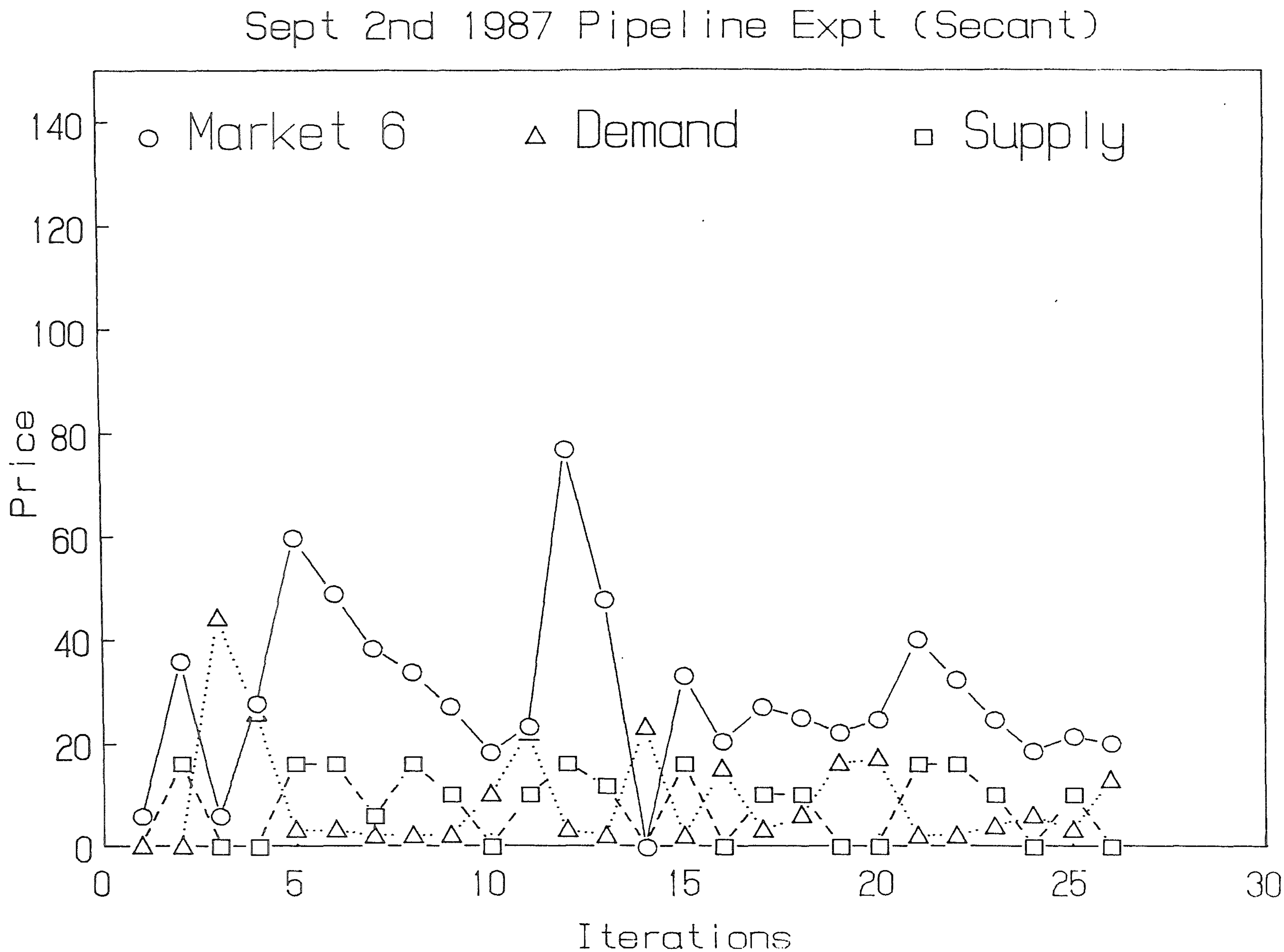
Sept 2nd 1987 Pipeline Expt (Secant)
Market 4
Demand
Supply
Price
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
100
50
0
5
10
15
20
25
30
Iterations

FIGURE: 4-E



Sept 2nd 1987 Pipeline Expt (Secant)
Market 5
Demand
Supply
Price
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Iterations

FIGURE: 4-F



Sept 2nd 1987 Pipeline Expt (Secant)
Market 6
Demand
Supply
Price
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Iterations

FIGURE: 4-G

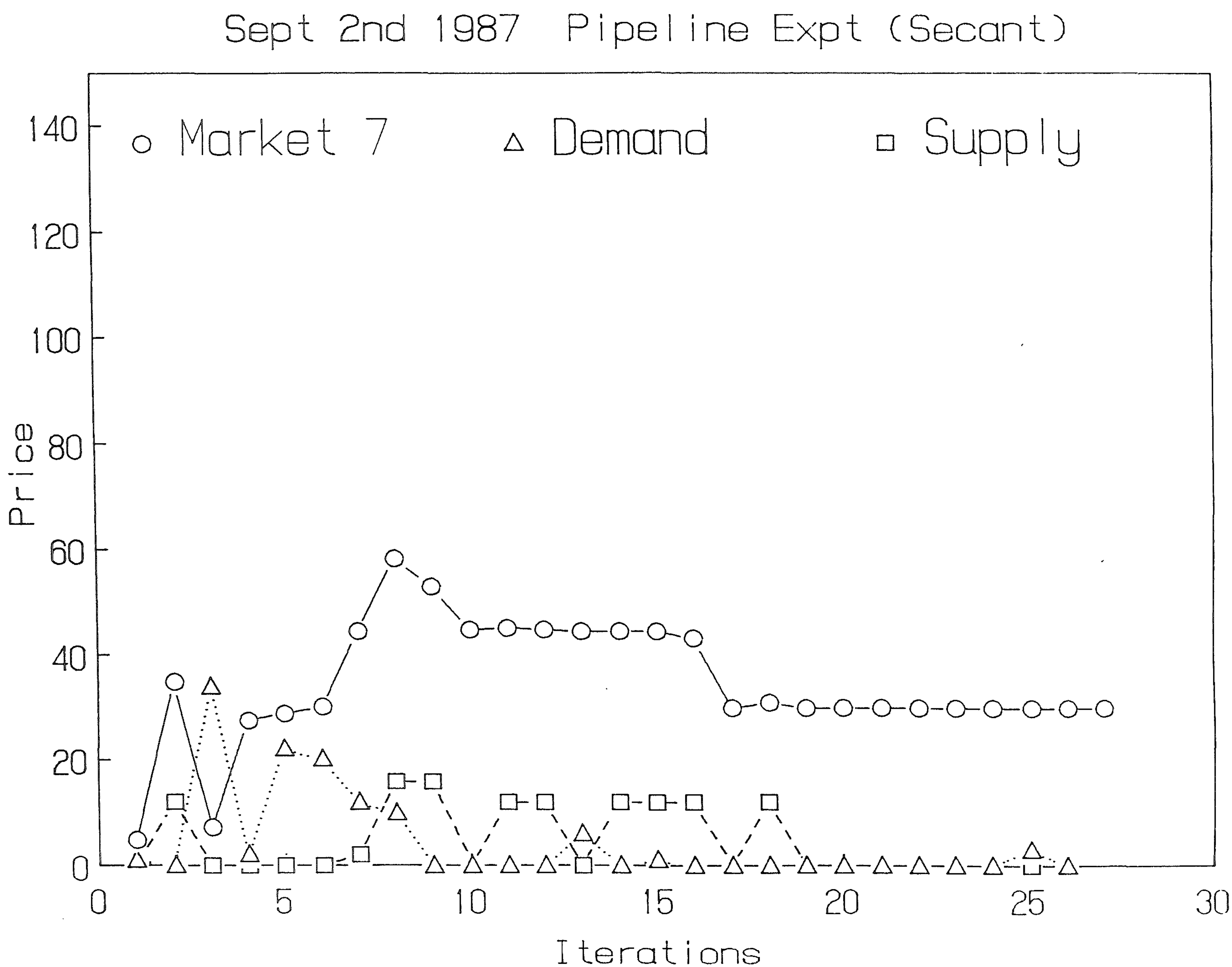

Sept 2nd 1987 Pipeline Expt (Secant)
Market 7
Demand
Supply
Price
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Iterations

FIGURE: 4-H

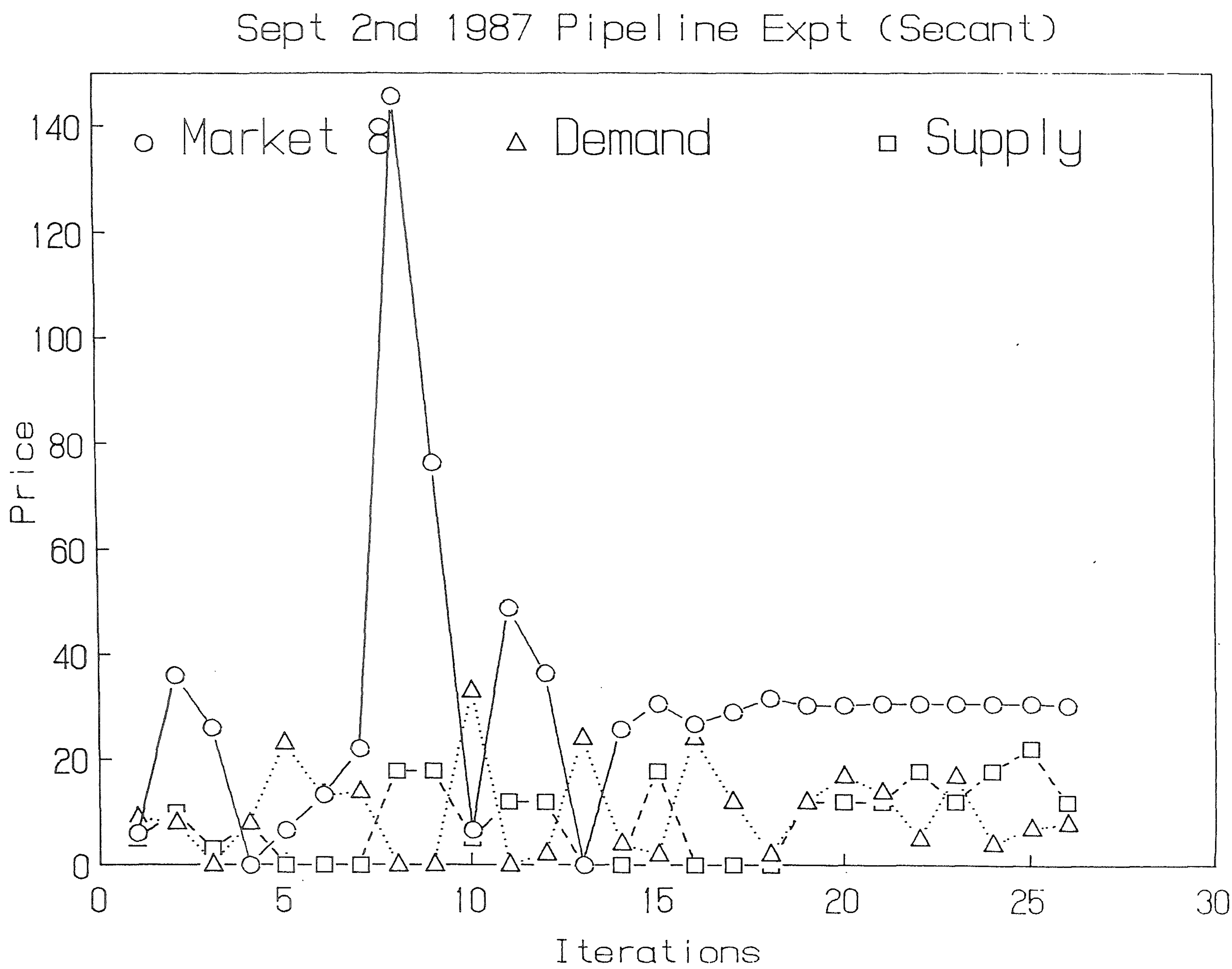
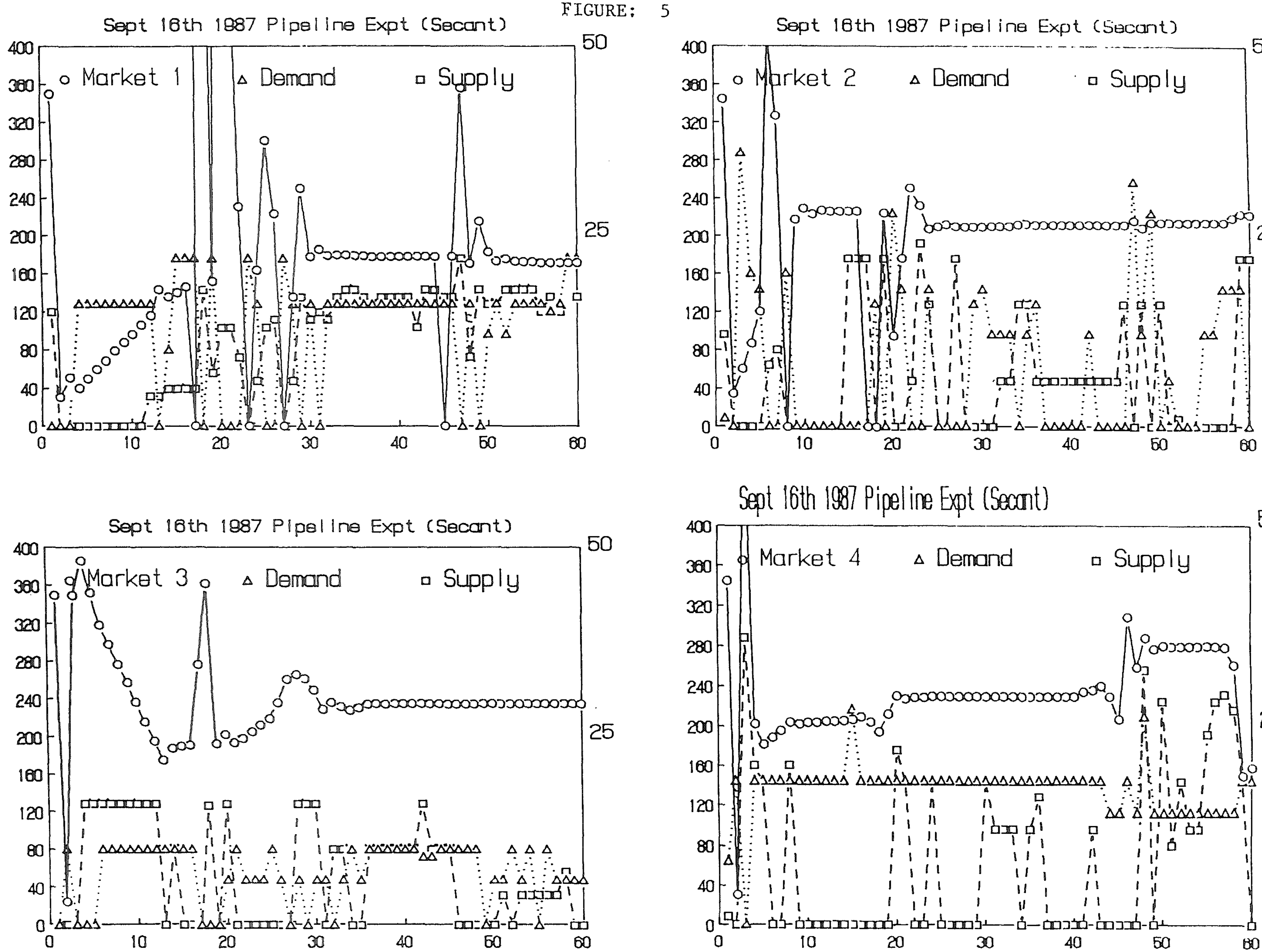

Sept 2nd 1987 Pipeline Expt (Secant)
Market 8
Demand
Supply
Price
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Iterations

FIGURE: 5


Sept 16th 1987 Pipeline Expt (Secant)
Market 1
Demand
Supply
Sept 16th 1987 Pipeline Expt (Secant)
Market 2
Demand
Supply
Sept 16th 1987 Pipeline Expt (Secant)
Market 3
Demand
Supply
Sept 16th 1987 Pipeline Expt (Secant)
Market 4
Demand
Supply

As can be seen in the figures, none of the markets equilibrated. Prices in the commodity markets 1, 2, 3, 4 tended to stabilize, but the expressed demands and supplies never equate. This is also true of Transportation Market 8. Transportation Market 7 is not used. Markets 5 and 6 show variability in all quantities. After twenty-seven iterations, the experiment was terminated.

After an additional attempt failed to foster convergence, a different approach was taken. The pipeline has a knife-edged equilibrium. If prices are exactly at equilibrium everything balances. However, a small deviation from equilibrium in the transportation market can cause a large increase in demand for pipeline transport. If the fee for transmission exactly equals the difference in commodity prices at the ends of the pipeline everything is in balance. If the difference in commodity prices is slightly above the transport fee then arbitrage profits are possible. Many agents attempting to capture those profits can create a large excess demand expressed for pipeline services.

The new approach permitted pipeline prices on a link to be the difference between the two commodity prices at the two ends of the link. This convention eliminated the need for prices in the pipeline markets to adjust independently. Instead, they are derived from commodity prices. Two experiments are reported under this convention. One used the secant method and the other used the proportional adjustment rule.

Since pipeline prices were derived, only the five commodity prices needed to be determined by the market. When the experiment was performed, the secant process operated for sixty iterations before the experiment was terminated without an equilibrium or allocation. The time paths shown in Figure 5 reveal stable prices (but not excess demands) in three markets and rather unresponsive prices for a long period in Market 4. This latter phenomenon is due to a small change in price about Period 8 being followed by a long string of constant excess demands. Recall, if excess demand remains constant, so does ΔP. About Period 50, Market 4 begins to move around, but then the other markets are not moving. No signs of convergence are evident.

The proportional rule was implemented in the same framework because the secant method did not seem to be sufficiently responsive. The results from the proportional adjustment rule are in Figure 6. Notice the wide swings of excess demand in Markets 2 and 4. By Period 50, no signs of convergence were apparent and the experiment was terminated.

Analysis after these two experiments yields no good theory about what might be wrong with the tâtonnement processes. In part, the problem could be related to the fact that expressed demands and supplies need not be binding. In addition, attempts by agents to get the process to stop, similar to the behavior observed in the one market case, can be a source of problems in multiple markets. Concessions can be made by agents to get one market to equilibrate, but given the nature of the process, there is no need to be bound by the concessions when the prices approach equilibrium in other markets. This process creates inconsistencies in the data used by the process which may be hard to overcome. Without a good theory of the problem, analysis of the processes was dropped.

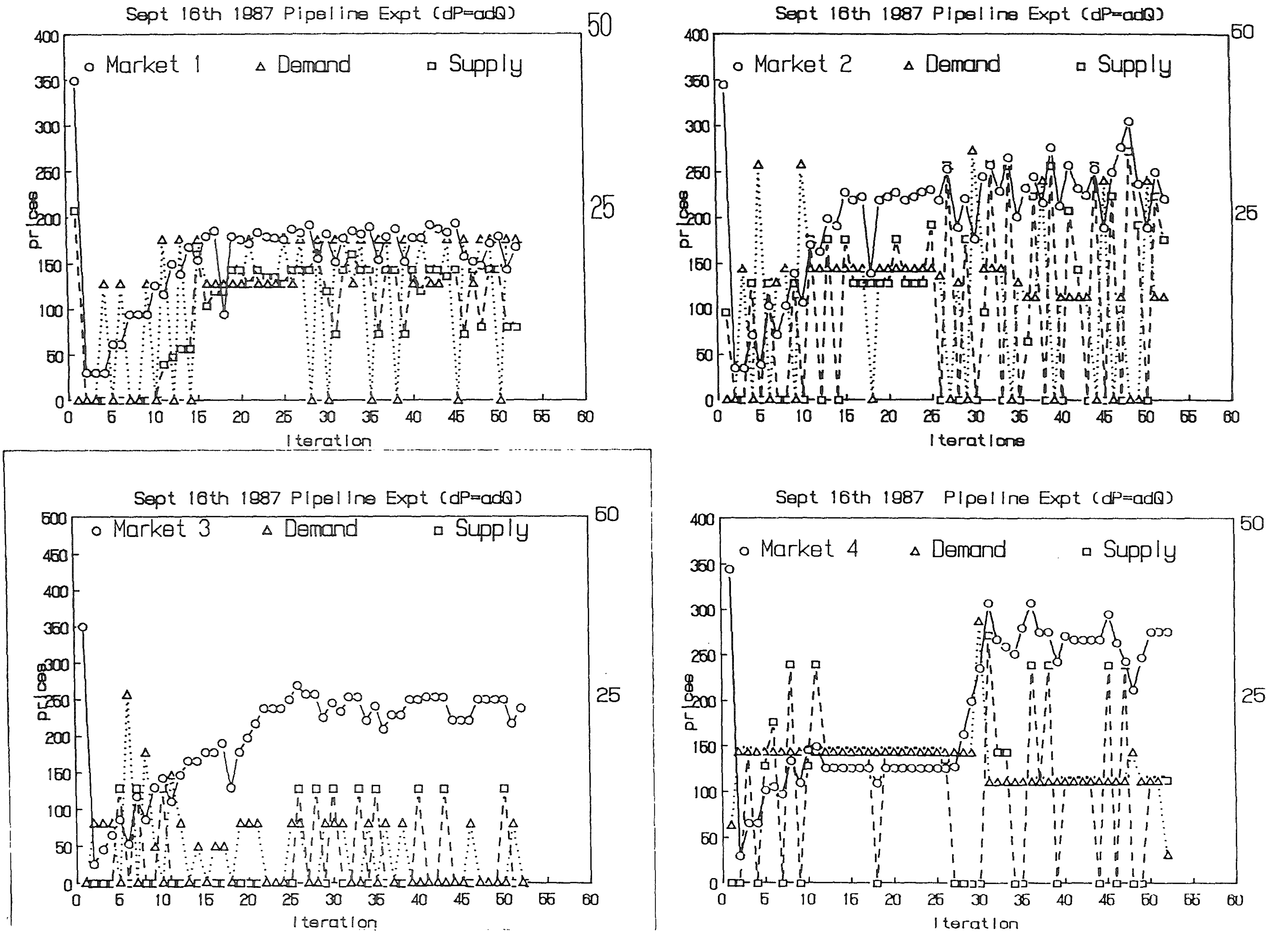
SECTION 4: AUTOMATED USER SELECTION MECHANISM (AUSM)

This process involved a computer assisted market for "packages" of commodity and transportation. Anyone can tender a bid to supply some resources and consume others. The bid can be positive or negative. The bid designates the amount desired of each commodity and each transportation link. A negative quantity indicates a supply.

The computer searches all bids to maximize total supplies of the system. It accepts the combination of bids that have the maximizing property. Agents who are not in the solution have the option of changing their bid and the computer tries to fit the new bid perhaps by bumping a previously (tentatively) accepted bid. The "bumped" agent can resubmit. The process continues until bidding stops.

One experiment was conducted. In this experiment no feasible solution was ever generated. Buyers bid too low and sellers asked too much. No feasible solution was attained so the

FIGURE: 6



Sept 16th 1987 Pipeline Expt (dP=adQ)
Market 1
Demand
Supply
prices
Iteration
Sept 16th 1987 Pipeline Expt (dP=adQ)
Market 2
Demand
Supply
prices
Iterations
Sept 16th 1987 Pipeline Expt (dP=adQ)
Market 3
Demand
Supply
prices
Iteration
Sept 16th 1987 Pipeline Expt (dP=adQ)
Market 4
Demand
Supply
prices
Iteration

process never got started even after 100 bids had been submitted. The research on this process was stopped until a better theory could be found.

SECTION 5: MULTIPLE DECENTRALIZED MARKETS

This phase of research explored a policy of multiple decentralized markets. Prices at every point are determined by the decisions of contracting parties unsupervised and unconstrained by administrative controls. No price limitations; ceilings and floors are improved. Prices do not result from an assessment of the market by an administrative source and a resulting decision about what an appropriate price might be, as was the case with tâtonnement processes. Instead, prices emerge from the hundreds of decisions made by contracting parties.

The policy as implemented in the experiment provided a specific form of organization within which negotiation and price determination take place. Technically, the term is a Multiple Unit Double Auction. This type of market process has been computerized so all bids/asks can be entered into personal computers that have been networked to facilitate interactions from remote locations. The computer publicly displays all bids/asks and contracts and performs the appropriate accounting and scheduling.

Several experiments were conducted within the small network; the results of which are not reviewed here. The results reported here are only those conducted in the larger more complicated network. Given the nature of the issues, the larger network provides a better source of data.

A total of nineteen markets were opened in each experiment. A separate market was organized for each of the nine location points. Prices quoted in Market *i* were for commodity for delivery at Point *i*. The commodity might have been produced at the point or it might have been transported there for sale. For example, prices quoted at Points 1 and 4 are ordinarily for commodity acquired at the producing field since those are the locations of fields, while commodity purchased and sold at Point F must have been transported there from some other location.

Similarly, a separate market was opened for each of the ten lines. Market 10, for example, contained price quotations for pipeline transportation from P1 to P2. In order to move commodity from one point in the network to another, pipeline services must be purchased separately for every line on the route connecting the two points. Purchase of the transportation services of pipelines involved a transaction in each of the separate markets over which transportation is desired.

Each market was an open market in the sense that anyone could tender a bid for the commodity or transport. A bid consisted of a per unit price and a total volume desired. Similarly, anyone with commodity or transportation capacity to sell could tender an ask which consisted of a price per unit and a volume offered for sale at that price per unit. The lowest bid and ask were displayed to the market on individual personalized computer screens.[7] If a better bid (higher unit price) or better ask (lower unit price) was tendered, it replaced the existing bid or ask on the screen.

Any agent was free to accept the displayed bid or ask or accept any part of it. This was done by simply entering the acceptance through his/her personal computer. The computer then executed the contract and sent the proper accounting messages throughout the network.

Each remote computer maintained the accounting and inventory for that person. The computer also displayed the bids and asks in all markets as well as the history of transactions in all markets.

Agents were free to buy and resell at the same location or any other location or any other combination of purchases and sales among locations. Producers could purchase transportation and ship product to a remote location for sale. Consumers could buy commodity at a remote location, acquire the transportation, and then ship the commodity to their home location for their own use or for resale to another consumer. Pipelines could buy in one location and sell in another, using their own pipeline exclusively or in combination with some other pipeline whose services had been purchased. In other words, agents were free to buy and sell in any way that they thought was in

7) In these markets, only the lowest bid or ask was accepted by the computer. No "book" or "limit order" was possible. Such features can easily be added.

their own interest.

Series 1. The Competitive Pipeline

A glance at the network in Figure 2 reveals that two pipelines connect each point. This could be interpreted as two sellers who have capacity rights over the same physical pipeline. Alternatively, it could be interpreted as two different routes between the points which are equivalent from an economic perspective. Or it could be interpreted as drawn in Figure 2—as two separate and competing lines connecting the points.

Notice also that no one pipeline company competes with the same competitor over all segments. No two companies are "side-by-side" everywhere and the ownership of pipelines, consumers, and producers is all separated.

Prices

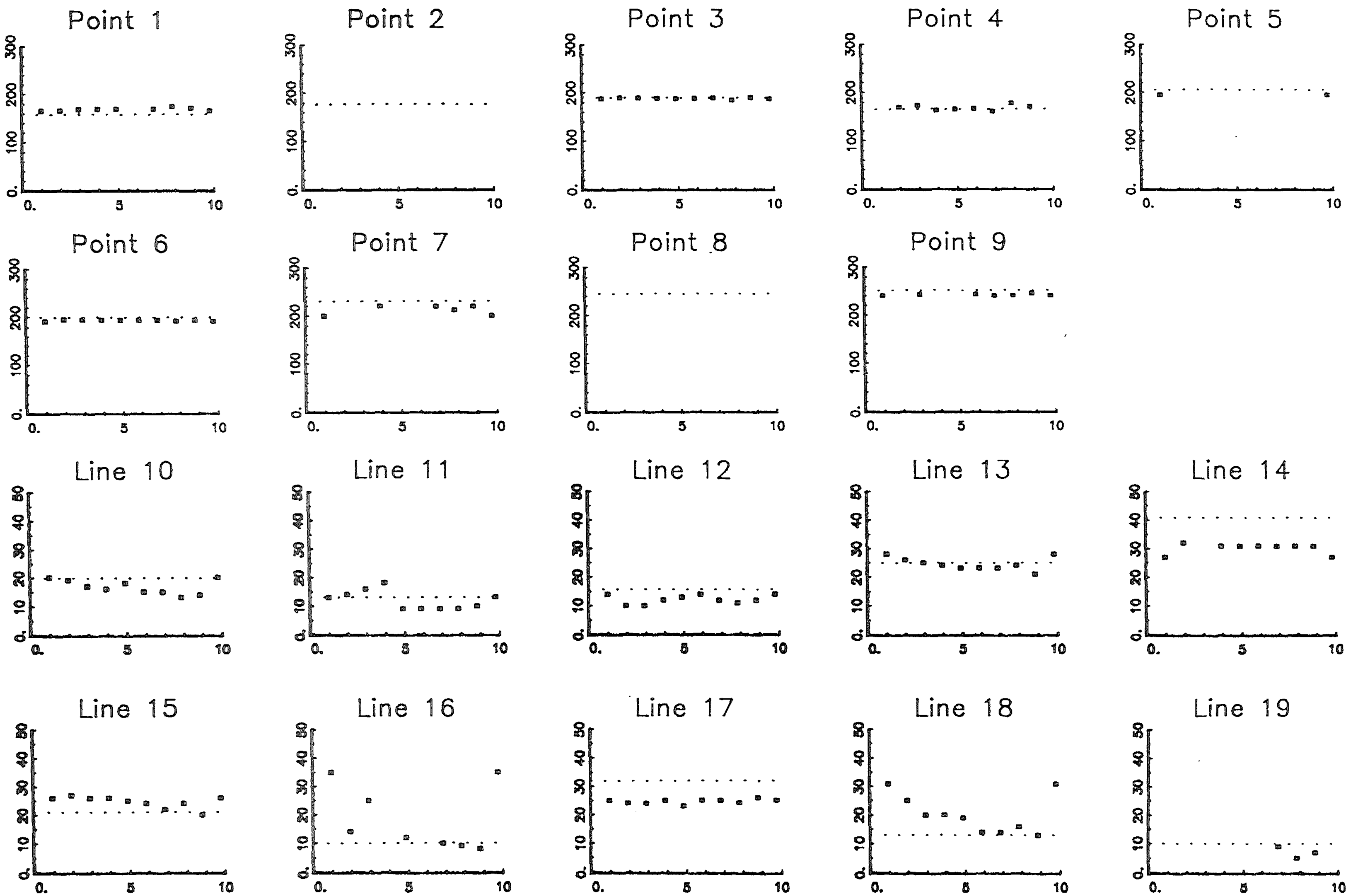
The results of six different experiments are contained in Figures 7-A through 7-E, along with the accompanying tables. All markets were open simultaneously for a series of periods after an initial orientation and practice period. Each period lasted for about fifteen minutes. Shown in the figures are the average prices for each period in each market. These are shown in relationship to the equilibrium prices of the competitive model. Notice that in some periods in some markets no transactions occur. This simply means that the producer or consumer at that location sold or purchased commodity at a remote location and moved the commodity himself.

The first three experiments (January 21, January 27, and February 3) involved agents with no experience at all. The next three experiments (February 8, February 10, and February 18) were almost all experienced from the earlier three and from experiments with the smaller network.

Notice first that the commodity prices tend to closely approximate the competitive equilibrium prices. Transportation prices show some variability but the averages can be misleading because of low volumes. The transporters could be moving the commodity themselves and not

FIGURE: 7-A

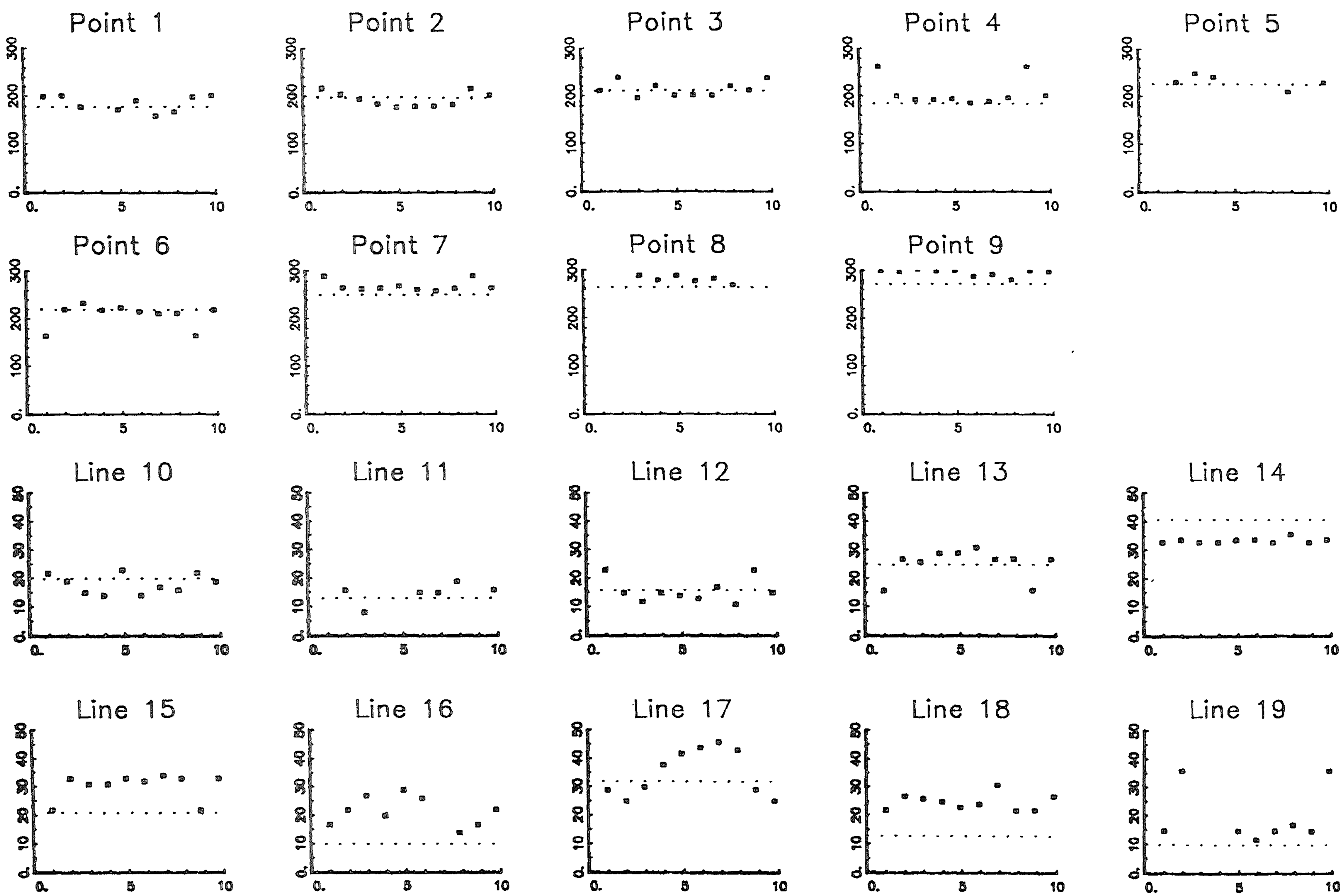
Mean Price by Period for All Markets(Jan. 27, 1988)



Note–X:Period Y:Mean Price

FIGURE: 7-B

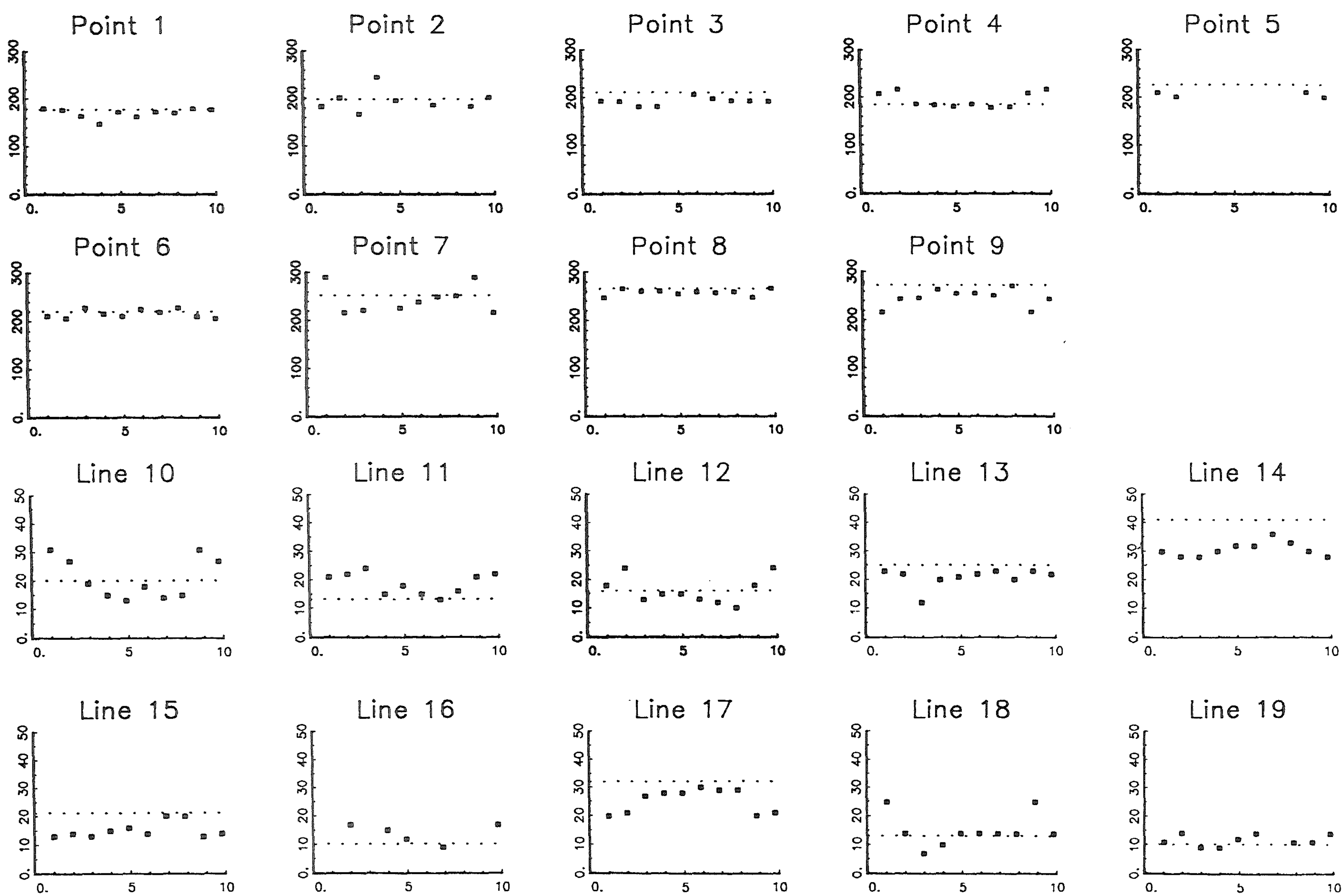
Mean Price by Period for All Markets(Feb. 3, 1988)



Note—X:Period Y:Mean Price

FIGURE: 7-C

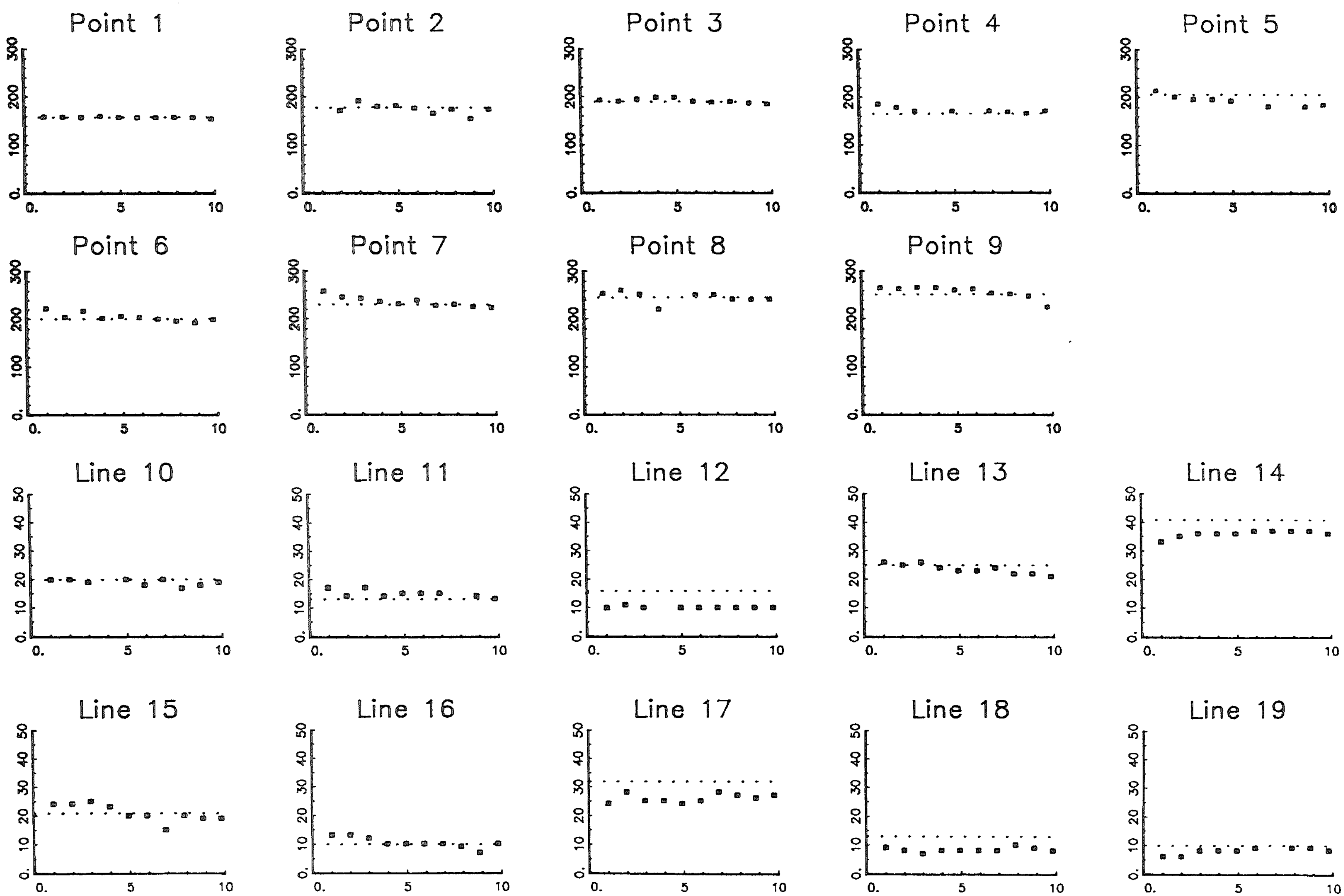
Mean Price by Period for All Markets(*Feb.* 8, 1988)



Note—X:*Period* Y:*Mean Price*

FIGURE: 7-D

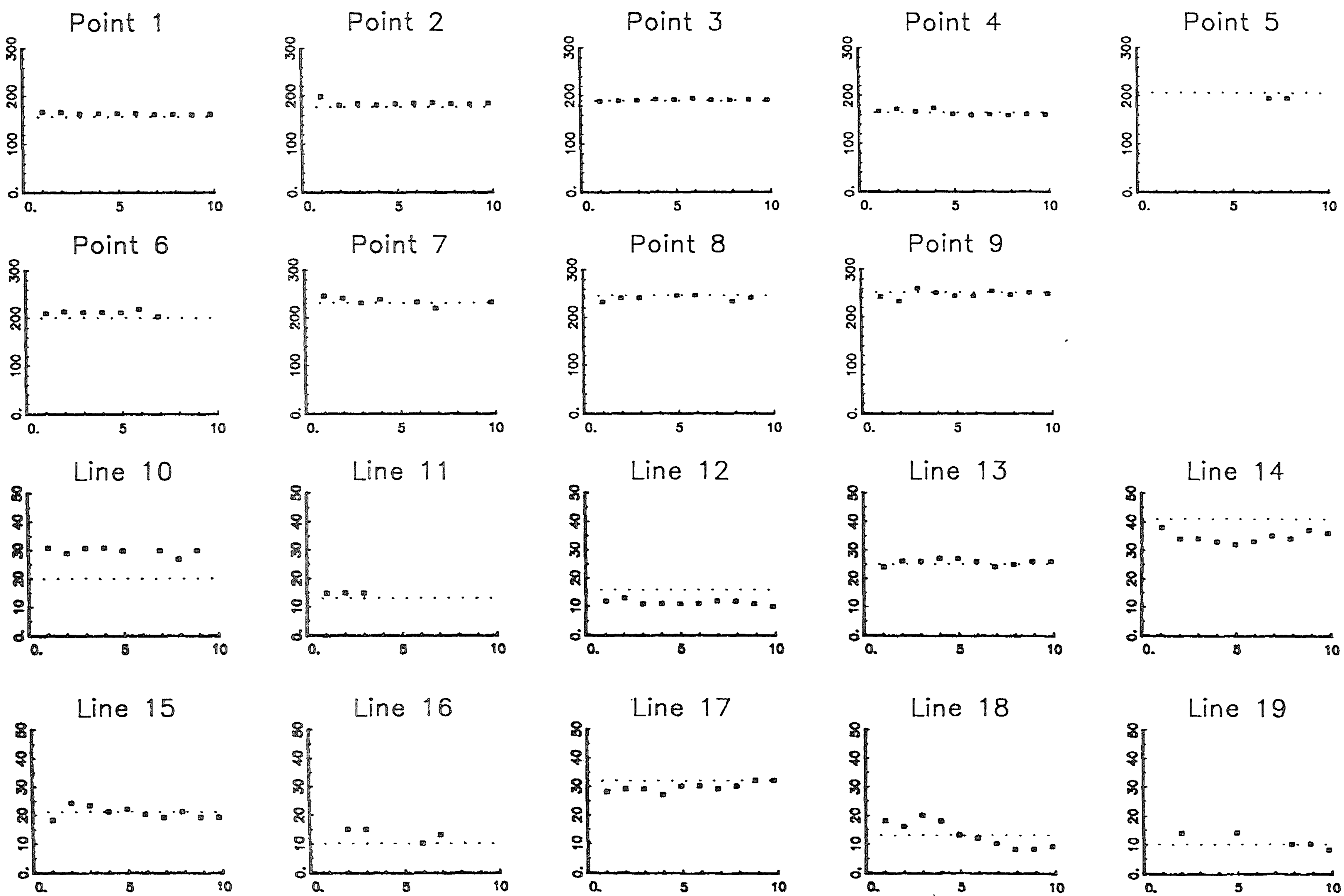
Mean Price by Period for All Markets(Feb. 10, 1988)



Note–X:*Period* Y:*Mean Price*

FIGURE: 7-E

Mean Price by Period for All Markets(Feb. 18, 1988)



Note—X:Period Y:Mean Price

selling the transportation on the open markets. The fact that the commodity is moving and that commodity prices are near the predicted equilibrium indicates that the transportation markets are working well despite what averages might indicate.

Perhaps the most interesting are the last two experiments in the series. These involved agents with the most experience. As can be seen, commodity prices and transportation prices closely approximate the competitive equilibrium.

Efficiencies

The efficiencies are in the Table 4. First notice that efficiencies can be negative. This can happen if commodity is produced and moved but not sold or used. In addition, transportation can be purchased but not used. Because of these features, the technical possibility exists that the system behaves very badly.

In fact, as can be seen, the system improves with use. Efficiencies tend to go up as a given set of agents gain expertise with the process. In all experiments, the efficiency of the last three periods is greater than the efficiency of the first three periods. Similarly, the efficiency of the last three experiments, those that had many already experienced agents, were greater than the first three. In fact, in experiments 2/10 and 2/18, efficiency increased to the high 80s and low 90s.

Series 2. Monopolized Pipelines

For purposes of studying the effect of monopoly, competitors in all links were merged. The resulting network is in Figure 8. The ownership and costs for the pipelines are in Table 5. The economic parameters are all the same. The location and demands of consumers are the same as in the previously studied Figure 2 and Table 2. The location and cost of producers are the same as before. The *total* capacity and cost of each link of the pipeline is the same as before. It is as though the previous two pipelines on a link are controlled by the same owner.[8] The markets are

8) In fact, two agents that formally competed now get together and share profits. They are organized so that the pair makes single decisions.

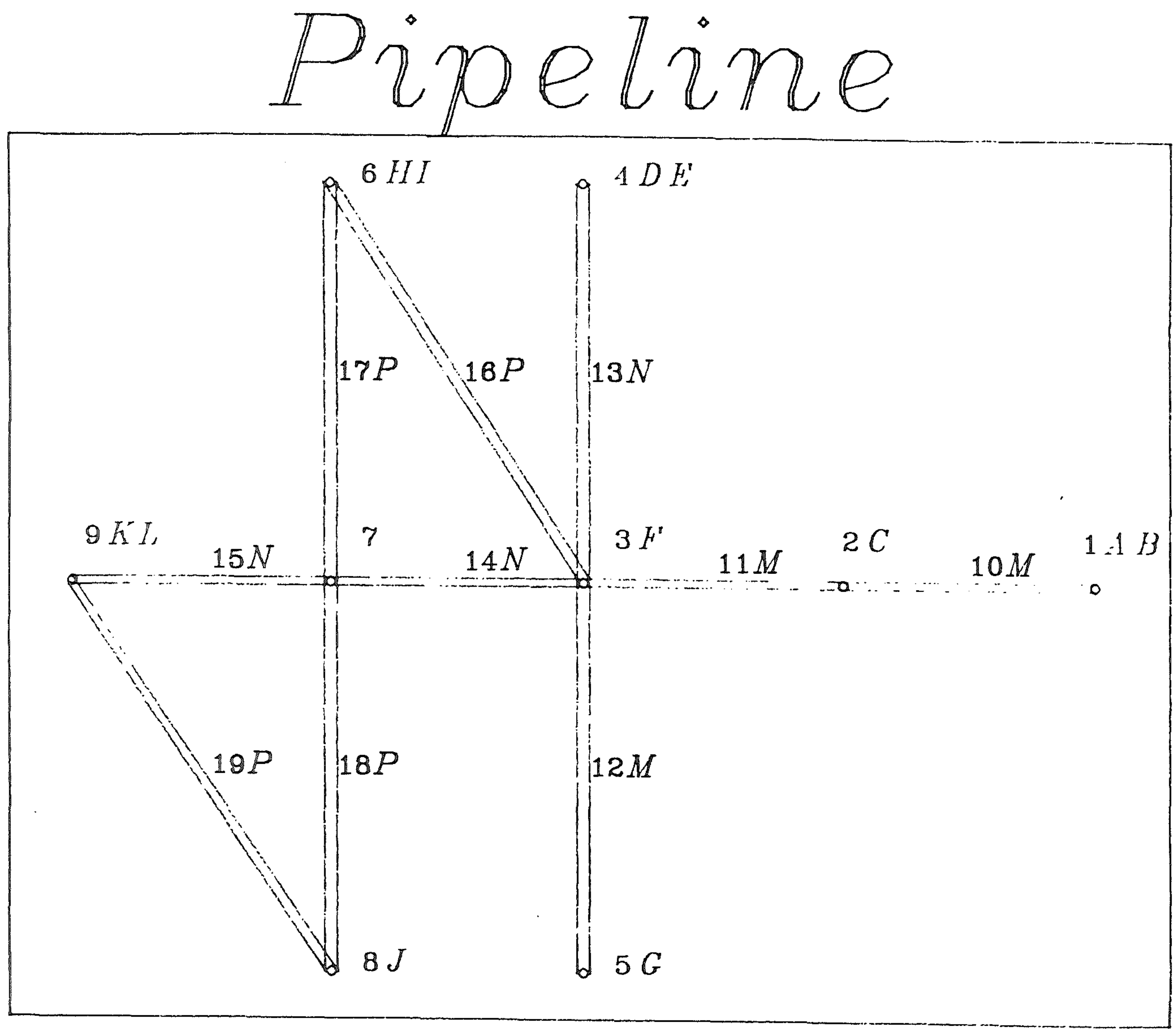
TABLE 4: Efficiency of Decentralized Markets in Competitive Network

Period	1-21	1-27	2-3	2-8	2-10	2-18
1	.61	.53	.44	-.59	.55	.50
2	.33	.73	.59	.44	.89	.77
3	.76	.77	.51	.64	.85	.83
4	.64	.83	.55	.72	.41	.82
5	.72	.78	.48	.54	.80	.71
6	.76	.80	.66	.88	.76	.85
7	1.00	.84	.70	1.00	.91	.75
8		.81	.56	.81	.82	.90
9		.80			.85	.92
10					.81	.90

TABLE 5: Pipeline Ownership in Monopolized Transportation Network

L10	M	pipeline	10,16 15,6
L11	M	pipeline	5,12 8,6
L12	M	pipeline	6,6 11,24
L13	N	pipeline	14,14 20,6
L14	N	pipeline	29,8 36,6
L15	N	pipeline	11,8 16,6
L17	P	pipeline	19,14 27,6
L18	P	pipeline	4,14 8,6
L19	P	pipeline	5,8 9,6

FIGURE: 8



Pipeline
6 HI
4 DE
17P
16P
13N
9 KL
7
3 F
2 C
1 A B
15N
14N
11M
10M
19P
18P
12M
8 J
5 G

organized exactly as before.

Two experiments were conducted. Agents were experienced from the earlier competitive pipeline experiments discussed in the section above. Consequently, the initial learning about the technology of the market was minimized. The franc values of the redemption values were changed (a constant of twenty francs was added to all redemption values and all gas production cost, but not pipeline cost) so the expectations built from previous experiments would not have a major influence. Participants did not know that the underlying economic parameters were exactly as before.

Results

The series of prices are shown in Figures 9-A and 9-B. The price scale on the transportation graphs is different from the corresponding figures in the competitive case, so direct visual comparison with the competitive figures might be misleading.

Notice first that commodity prices are near the competitive equilibrium. Transportation prices are substantially above the competitive equilibrium.

Efficiencies are in Table 6. As was the case in the competitive networks, efficiencies begin low and increase as experience is gained and prices converge to predictable patterns. For the most part, the efficiencies attained are in the 70s.

Not shown in the graph is the degree to which the inefficiency occurred as a result of withheld capacity by the monopolists. It is possible that transportation prices are high, but, nevertheless, the commodity can be efficiently moved; all of the capacity is used by the pipeline itself. Inefficiencies in this case would result from attempts to transport by outsiders who purchase transport on some links, get frozen out by high prices on others, and, as a result, waste the capacity and sometimes the product. At this time, the analysis to isolate the sources of inefficiency has not been performed.

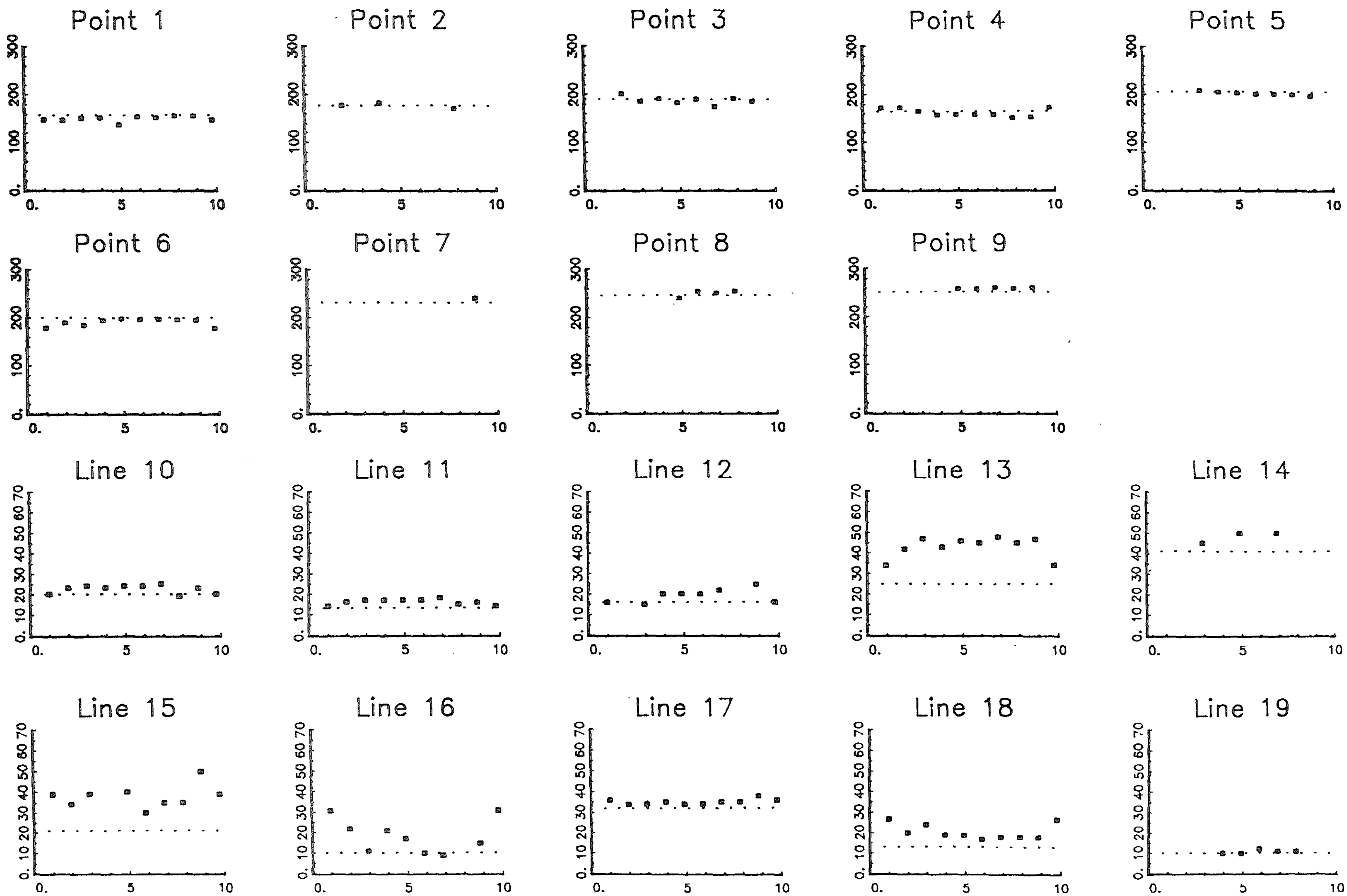
TABLE 6: Monopolized Network Efficiencies

Period	3-4 #1	3-4 #2
1	.66	-.01
2	.31	.25
3	.71	.32
4	.39	.67
5	.69	.86
6	.75	.75
7	.72	.80
8	.79	.64
9	.85	.69
10		.65
11		.76

FIGURE: 9-A

Mean Price by Period for All Markets(*Mar.* 3, 1988 #1)

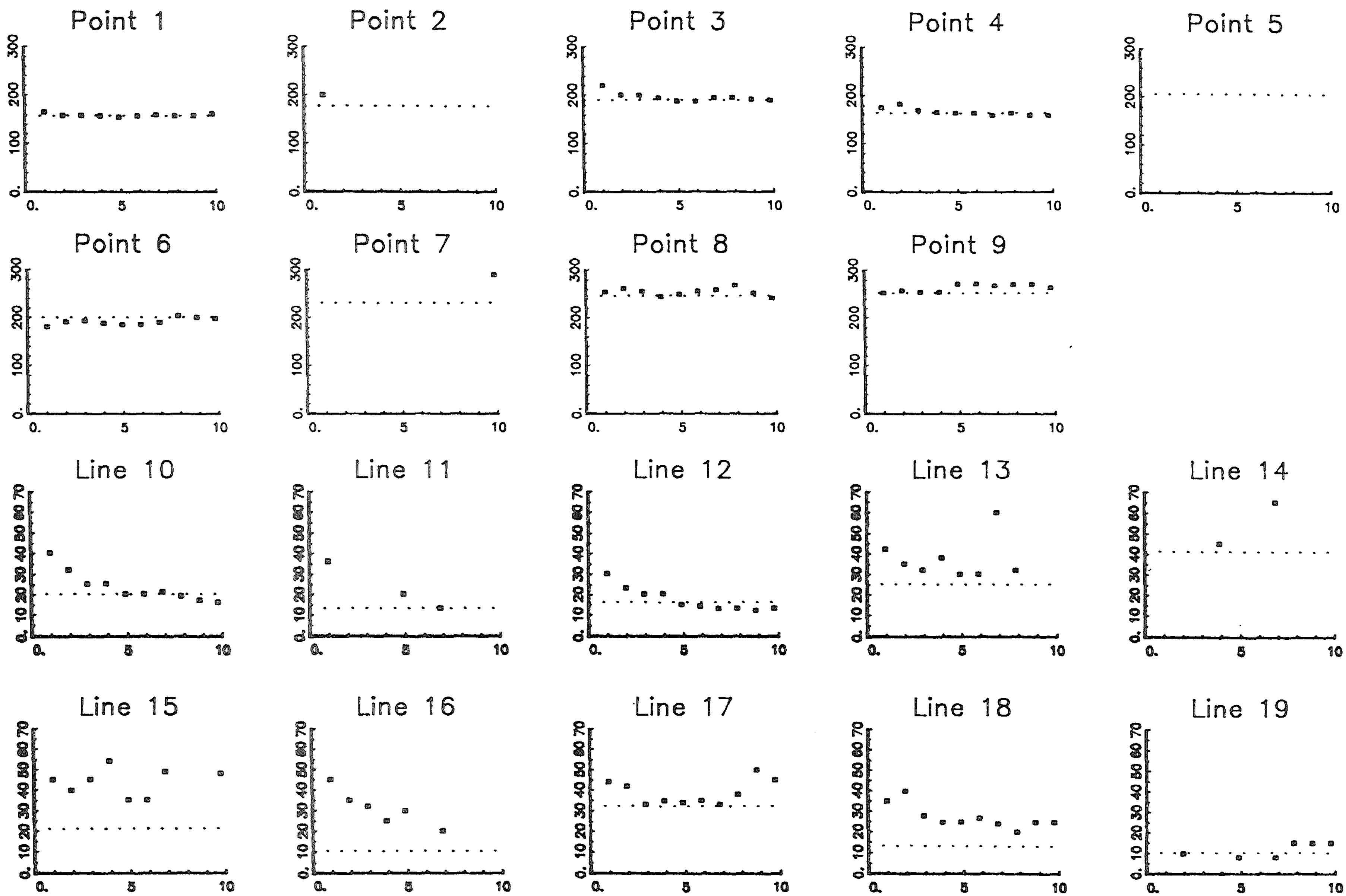
With Transportation Monopolized



Note—X:*Period* Y:*Mean Price*

FIGURE: 9-B

Mean Price by Period for All Markets(Mar. 3, 1988 #2)
With Transportation Monopolized



Note—X:Period Y:Mean Price

Comparison of Monopoly and Competition

The effects of competition can be most easily seen in two measures: efficiency and relative profits. The results on efficiency are easy to see. The test comparison is after time is allowed for market adjustments in the later periods. In the later periods of competitive markets, the efficiencies are in the high 80s. In the later periods of monopoly, the efficiencies are in the high 60s and low 70s.

The differential in efficiencies is due in part to the interdependent nature of the network. High, monopolized prices on one leg of a market prevent the downstream benefits of possibly increased commodity flow. The effects of a "bottleneck" in one segment have impacts elsewhere.

The second measure of profits is presented in Table 7. Computed there are the average profits in the final periods of the final two competitive pipeline experiments and the two monopolized pipeline experiments. The profits of consumers, producers, and transporters are reported as groups. The profits predicted by the competitive equilibrium model are also presented.

Notice first that the actual incomes of each group under conditions of pipeline competition (duopoly) compare favorably with the magnitudes predicted by the competitive equilibrium model. In all cases, profit falls short by comparable magnitudes (.07, .13, and .08 for consumers, producers, and transporters, respectively).

Under monopoly, the deviations from the competitive model are more dramatic. Consumer profits are .51 less than the profits predicted by the competitive model. Producer profits are .33 less than the predicted profits, but the average profits of transporters are .04 less than predicted by the competitive model.

It is of interest to note that the effect of monopoly is to hurt consumers and producers, but it does not particularly benefit the pipeline owners. Profits of the pipelines remain essentially the same. Under monopoly, pipelines prosper more relative to consumers and producers, but relative to profits when competition exists over the pipeline, the pipeline profit position is about the same.

TABLE 7: Total Profit Per Period in Final Periods of Selected Experiments

	Consumers	Producers	Transporters
Competitive EQ Model	1246	1510	1118
Actual Competitive Pipelines	1154	1313	1032
Actual Monopoly Pipeline	607	1009	1064

The reason for this paradox is that the efficiency falls under monopoly. The fall is damaging to the whole industry. The total efficiency of the pipeline falls under monopoly and monopoly pipelines simply manage to hold on to their share.

SUMMARY AND OVERVIEW

Several major questions can be posed of the research. These will be reviewed.

1. Will a tâtonnement process work in a complex network?

   The ideas behind the tâtonnement process can be made sufficiently precise to implement operationally. The process itself seems to work adequately in single markets. However, the transition of the process to multiple markets was not successful. The reasons for the failure are not clear. Attempts to remove some of the flexibility and provide greater coordination of price changes failed to produce a workable process. Attempts to make price changes more flexible to market conditions also failed to produce a workable process. Time prevented a pursuit of other ideas about what might make this process work.

2. How good is the generalized Automated User Selection Mechanism?

   It did not work to produce an allocation. There are reasonable conjectures about how this process might be made to work. They have not been pursued.

3. How does the decentralized market process work?

   a. It is clear that decentralized markets can coordinate to move the product. The interdependence inherent in a pipeline network does not prevent this.

   b. The commodity moves smoothly with no evidence of instability.

   c. Under conditions of some competition (duopoly) over all lines, prices approach the general competitive equilibrium levels. System efficiencies are high and improve with operation into the high 80 or 90 percentages. The inefficiencies that remain might be avoided by appropriate contingent contracts which permit plans to be developed without contracts being firm.

d. When there is no competition in the network, the influence of monopoly can be detected. Efficiencies fall and the impact of the reduced efficiency falls on consumers and producers.

4. How do the policies deal with uncertainties and the distinction between interruptible and firm? These experiments were not designed to deal with that problem. The theory that was successful in predicting the system behavior in the decentralized markets suggests that the uncertainty can be incorporated without problems. The experiments have not been conducted.

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